An exergy based method for resource accounting in factories

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Abstract

In the current global climate of declining fossil fuel reserves and due to the impact of industry on the natural environment, industrial sustainability is becoming ever more important. However, sustainability is quite a vague concept for many, and there are a range of interpretations of the word. If the resource efficiency of a factory is taken as a measure of its sustainability, then the concept becomes better defined and quantifiable. In order to analyse the resource efficiency of a factory and suggest improvements, all flows through the manufacturing system need to be modelled. However the factory is a complex environment, there is a wide variation in the quality levels of energy as well as the composition of material flows in the system. The research presented in this thesis shows how the thermodynamics-based concept of 'exergy' can be used to quantify the resource efficiency of a factory. The factory is considered an 'integrated system', meaning it is composed of the building and the production processes, both interacting with each other. This is supported by three case studies in different industries that demonstrate the practical application of the approach.

A review of literature identified that it was appropriate to develop a novel approach that combined exergy analysis with the integrated view of the factory. Such an approach would allow a 'holistic' assessment of resource efficiency for different technology options possibly employable. The development of the approach and its illustration through practical case studies is the main contribution of the work presented.

Three case studies, when viewed together, illustrate all aspects of the novel exergy based resource accounting approach. The first case study is that of an engine production line, in which the resource efficiency of this part of the factory is analysed for different energy system options relating to heating ventilation and air conditioning. Firstly, the baseline is compared with the use of a solar photovoltaic array to generate electricity, and then a heat recovery unit is considered. Finally, both of these options were used together, and here it is found that the non-renewable exergy supply and exergy destruction are reduced by 51.6% and 49.2% respectively.

The second case study is that of a jaggery (a sugar substitute) production line. The exergy efficiency of the process is calculated based on varying the operating temperature of the jaggery furnace. The

case study describes the modelling of al flows through the jaggery process in terms of exergy. Since this is the first example of an exergy analysis of a jaggery process, it can be considered a minor contribution of the work. An imaginary secondary process that could utilize the waste heat from the jaggery process is considered in order to illustrate the application of the approach to industrial symbiosis. The non-renewable exergy supply and exergy destruction are determined for the baseline and the alternative option. The goal of this case study is not to present a thermally optimized design; rather it illustrates how the exergy concept can be used to assess the impact of changes to individual process operations on the overall efficiency in industrial symbiosis.

When considering natural resource consumption in manufacturing, accounting for clean water consumption is increasingly important. Therefore, a holistic methodology for resource accounting in factories must be able to account for water efficiency as well. The third case study is that of a food production facility where the water supply and effluent are modelled in terms of exergy. A review of relevant literature shows that previously, the exergy content of only natural water bodies and urban wastewater had been quantified. To the author's knowledge, this is the first example of applying this methodology of modelling water flows in a manufacturing context. The results show that due to a high amount of organic content in food process effluent, there is significant recoverable exergy in it. Therefore, a hypothetical water treatment process was assumed to estimate the possible savings in exergy consumption. The results show that at least a net 4.1% savings in terms of exergy could be possible if anaerobic digestion water treatment was employed. This result can be significant for the UK since the food sector forms a significant portion of the industry in the country.

Towards the end of the thesis, a qualitative study is also presented that aims to evaluate the practical utility of the approach for the industry. A mixed method approach was used to acquire data from experts in the field and analyse their responses. The exergy based resource accounting method developed in this thesis was first presented to them before acquiring the responses. A unanimous view emerged that the developed exergy based factory resource accounting methodology has good potential to benefit industrial sustainability. However, they also agreed that exergy was too complex a concept to be currently widely applied in practice. To this effect, measures that could help overcome this barrier to its practical application were presented which form part of future work.

Dedication

To my late big brother, Rambail Ibrar Khattak, the person I loved and admired the most. His love for life, beauty in persona and strength in character will always be remembered. May you rest in the best of places.

Acknowledgements

Undertaking this PhD has truly been a life changing experience for me and it would not have been possible to do without the support of many people.

First and foremost, I would like to thank my supervisor Dr. Rick Greenough who made is possible for me to succeed in this journey. I am sincerely grateful to him for all his support and guidance through this long and tough period of my life. I greatly appreciate the financial support I received through the KAP and REEMAIN projects, which also provided invaluable experience. I am also thankful to Neil Brown, my second supervisor who has helped me when I needed it. Many thanks also to friends and colleagues at IESD, especially Dr. Ivan Korolija. I must also thank here Dr. Alicia Valero Delgado of the CIRCE institute at the University of Zaragoza, Spain. My chapter on modelling water flows through the factory would not have been possible without her support. This section would not be complete without me expressing my gratitude for my close family; my parents who supported me throughout and my wife and kids for making the journey a pleasure.

Finally, thanks to almighty Allah, the source of all knowledge, provider of all sustenance and the best of writers. I hope to be guided by Allah in the future, to progress my career and influence the earth in a positive way through my profession.

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Table of Nomenclature

S/N	Symbol/Formula	Explanation
1	A	Reactant of a chemical reaction
2	B	Reactant of a chemical reaction
3	b	Specific chemical exergy
4	C	Chemical concentration
5	c_{air}	Specific heat capacity of air
6	c_{water}	Specific heat capacity of water
7	e	Specific energy
8	E	Energy
9	$\dot{E}_{electrical}$	Electrical energy flow rate
10	$\dot{E}_{bagasse}$	Energy rate of bagasse supply
11	$\dot{E}_{evap}$	Energy rate of evaporated steam
12	$\dot{E}_{pre-heat}$	Rate of energy supplied for sensible heating of juice before evaporation
13	$\dot{E}_{jaggery}$	Energy rate of heat content of jaggery produced
14	$\dot{E}_{flue}$	Energy rate of flue gas
15	$\dot{E}_{ash}$	Energy rate of bagasse ash
16	$\dot{E}_{unburnt}$	Energy rate of un-burnt fuel
17	$\dot{E}x_{air}$	Exergy rate of air supply
18	$\dot{E}x_{ash}$	Exergy rate associated with bagasse ash
19	$\dot{E}x_{bagasse}$	Exergy rate of bagasse supply
20	$Ex_{Chemical}$	Total chemical exergy
21	$\dot{E}x_{chemicals}$	Exergy rate of chemicals inflow to system
22	$Ex_{concentration}$	Concentration exergy
23	$ex_{concentration}$	Specific concentration exergy
24	$\dot{E}x_{dest}$	Non-renewable exergy destruction rate
25	$\dot{E}x_{elec}$	Electricity supply rate
26	$Ex_{formation}$	Exergy of formation

27	$ex_{formation}$	Specific exergy of formation
28	$\dot{E}x_{flue}$	Exergy rate of flue gas
29	$\dot{E}x_{fr}$	Exergy of floating residue flow rate
30	$\dot{E}x_{gains}$	Rate of exergy gains to the HVAC system from factory components
31	$Ex_{heat\ flow}$	Heat flow exergy
32	$\dot{E}x_{in-air}$	Factory space supply air flow rate
33	$\dot{E}x_{in}$	Total exergy flow rate into the system
34	$\dot{E}x_{jaggery}$	Exergy rate associated with jaggery produced
35	$\dot{E}x_{juice}$	Exergy rate of juice flow into system
36	$Ex_{kinetic}$	Kinetic exergy
37	$ex_{kinetic}$	Specific kinetic exergy
38	$\dot{E}x_{out}$	Total exergy flow rate out of the system
39	$\dot{E}x_{out-air}$	Hot air supply rate delivered by the HVAC system
40	$Ex_{potential}$	Gravitational potential exergy
41	$ex_{potential}$	Specific gravitational potential exergy
42	$\dot{E}x_{PV,HVAC}$	Photovoltaic power supply to HVAC system
43	$\dot{E}x_{recov}$	Exergy recovery rate
44	$\dot{E}x_{supply}$	Non-renewable exergy supply rate
45	$Ex_{thermo-mechical}$	Thermo-mechanical exergy
46	Ex_{total}	Total exergy of a system
47	ex_{total}	Total specific exergy
48	$\dot{E}x_{total\ elec}$	Total electricity demand rate of the factory
49	$\dot{E}x_{vapour}$	Exergy rate of evaporated steam
50	$\Delta\dot{E}x_{wa}$	Water flow exergy supply rate
51	$\dot{E}x_{wall-losses}$	Exergy rate of heat lost through furnace walls
52	ΔEx_{work}	Work flow exergy
53	$\overline{G}$	Entransy
54	G	Gibb’s free energy
55	ΔG^0	Gibb’s free energy at standard conditions

56	h	Specific enthalpy of steam flow
57	h_0	Specific enthalpy of water at exergy references environment conditions
58	h_{fg}	Enthalpy of vaporization
59	L	The product of a chemical reaction
60	$\boldsymbol{m}$	Mass
61	n	Number of moles
62	$\dot{m}_{ash}$	Rate of bagasse ash mass produced
63	$\dot{m}_{bagasse}$	Bagasse supply mass flow rate
64	$\dot{m}_{chemical\,\&\,okra}$	Mass of chemicals and okra supply rate
65	$\dot{m}_{flue}$	Mass of flue gas flow rate
66	$\dot{m}_{fr}$	Mass of floating residue flow rate
67	$\dot{m}_{jaggery}$	Mass of jaggery production rate
68	$\dot{m}_{juice}$	Juice mass flow rate
69	$\dot{m}_{outside}$	Mass flow rate of supply air from outside natural environment
70	$\dot{m}_{steam}$	Mass flow rate of water evaporated
71	$\dot{m}_{wa}$	Mass flow rate of water
72	P	Pressure
73	Q	Heat flow
74	Q_H	Heat supply from a high temperature reservoir
75	Q_L	Heat flow into a low temperature reservoir
76	$\dot{Q}_{losses}$	Heat flow rate of wall energy losses
77	Q_{rad}	Radiation heat flow
78	R	Universal gas constant
79	s	Specific entropy
80	s_0	Specific entropy at references environment conditions
81	ΔS	Entropy change
82	T	Temperature of the system
83	T_0	Temperature at references environment conditions
84	$T_{jaggery}$	Temperature of jaggery produced

85	U	Internal energy
86	$\boldsymbol{V}$	Volume
87	v	Specific volume
88	$\vec{V}$	Velocity
89	W	Work
90	x	Stoichiometric concentration of chemical reactant
91	y	Stoichiometric concentration of chemical reactant
92	y_i	Molar fraction
93	z	Stoichiometric concentration of chemical product
94	$(NCV)_0$	Net calorific value at standard conditions
95	$\emptyset_{dry}$	The ratio of the chemical exergy to the net calorific value
96	φ	Fraction of renewable sourced thermal exergy in factory air
97	σ	Fraction of air exergy in total

Glossary of key terms in the thesis

S/N	Term	Definition
1	Closed loop	It refers to a concept in which resources are continuously reused in order to reduce waste
2	Cost benefit analysis	It is a systematic approach to estimating the strengths and weaknesses of alternatives that satisfy transactions, activities or functional requirements for a business.
3	Efficiency	A performance indicator that is the ratio of the useful output of a process to its supplied input.
4	Emergy	It is the total energy that the production of material, energy or service is needed directly and Indirectly, expressed in a same unit as solar emjoules (sej).
26	Energy	It is the capacity to do work.
5	Energy analysis	The analysis of energy flows through a system or process is termed as energy analysis.
31	Enthalpy (H)	H=U+pV, where U is the internal energy, p pressure and V volume. Its change gives the heat at constant pressure when there is no other work
6	Entransy	It is based on an analogy between thermal and electrical systems and corresponds to the electrical energy stored in a capacitor.
7	Entropy	It is a thermodynamic quantity that expresses the degree of disorder or randomness in a system.
21	Equilibrium	A state of balance, which effectively means no ability to cause change.
8	Exergoeconomic analysis	This is an analysis technique that combines the concepts of exergy and economics.
9	Exergy	The maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only
10	Exergy analysis	The analysis of exergy flows and consumption through a

		thermodynamic system is called exergy analysis
11	Exergy destruction	This is the consumption of exergy associated with the irreversibilities in a process
12	Extended exergy analysis	This is an extension of traditional exergy analysis to highlight the primary production factors, including labour and capital, and the exergy, necessary materials and environmental remediation.
29	First law of thermodynamics	This fundamental law states that in closed system the internal energy can be changed by work or heat only, i.e., $\Delta U = q+w$
13	Gibbs energy	It is defined as G=H-TS, where H denotes enthalpy, T the thermodynamic temperature and S the entropy. The change in Gibbs energy at constant pressure and temperature gives the maximal work available. In a closed system at constant pressure and temperature the Gibbs energy decreases during a spontaneous process
27	Heat	It is an energy transfer induced by temperature difference
14	Heat engine	A heat engine is a system that converts heat or thermal energy to mechanical energy, which can then be used to do mechanical work, while operating in a thermodynamic cycle.
15	Industrial ecology	It is defined as the study of interactions and interrelationships both within industrial systems and between industrial and natural systems
16	Industrial symbiosis	This terms represents a collection of industrial systems that exchange energy and material with each other to maximize resource efficiency
27	Internal energy	Is the total energy of the system. It contains the translational, rotational, vibrational, electronic, and nuclear energies and the energies due to intermolecular interactions. Its absolute value is unknown, its change is defined by the first law of thermodynamics. It is a state function and an extensive quantity.
17	Life cycle assessment	This is a well-established systematic approach used for the identification, quantification, and assessment of environmental impacts throughout the life cycle of an activity, product or processes.
18	LowEx	It is a concept that aims to reduce the exergy consumption in

		building through energy quality matching between supply and demand. Q
19	Physical hydronomics	The application of the exergoecological discipline to the natural resource “water” is termed as physical hydronomics
30	Reversible process	It is a process in which the system is always infinitesimally close to equilibrium. Such a process can never be observed, it is only of theoretical interest
32	Second law of thermodynamics	This law states that in isolated systems the entropy increases in spontaneous processes, i.e., $\Delta S > 0$; in reversible process at equilibrium it is constant, i.e., $\Delta S = 0$. or It is impossible to convert heat completely into work. or Heat cannot spontaneously flow from a material at lower temperature to a material at higher temperature
22	Technical building services	It refers to the implementation of the engineering for the internal environment and environmental impact of a building
20	Thermal reservoir	It is a thermodynamic system with a heat capacity that is large enough that when it is in thermal contact with another system of interest or its environment, its temperature remains effectively constant
23	Thermodynamic cycle	It is a series of thermodynamic processes which returns a system to its initial state
24	Thermodynamic reference environment (Szargut’s)	It is determined by the natural environment and can be assimilated to a thermodynamically dead planet where all materials have reacted, dispersed and mixed.
25	Work	is the scalar product of the applied force and the displacement of the object (in the direction of force)

Acronyms used in the thesis

S/N	Acronym	Definition
1	AFMBR	Anaerobic fluidized membrane bioreactor
2	AHU	Air handling unit
3	BMS	Building management system
4	CBA	Cost benefit analysis
5	CExC	Cumulative exergy consumption
6	DOAS	Dedicated outdoor air system
7	ECEEE	European council for energy efficient economy
8	EEA	Extended exergy analysis
9	EIA	The U.S. Energy information administration
10	EU	European union
11	ExLCA	Exergy life cycle assessment
12	HRU	Heat recovery unit
13	HVAC	Heating ventilating and air conditioning system
14	IE	Industrial ecology
15	IEA	International energy agency
16	IS	Industrial symbiosis
17	KAP	Knowledge, awareness, and prediction of man, machine, material in manufacturing
18	MEW	Material, energy and waste
19	OECD	Organisation for Economic Co-operation and Development
20	RE	Reference environment
21	TBS	Technical building services
22	UH	Unit heaters
23	WAGES	Water, air, gas, electricity and steam.

Chapter 1 Introduction

1.1. Chapter overview

This chapter provides an overview of the thesis and it explains the need for conducting the research. The delivered outcomes of the PhD project are listed where the central contribution of this work is a method for analysing industrial sustainability, based on the concepts of exergy and industrial ecology. The factory is viewed as an integrated system comprised of the manufacturing processes and the building. The approach therefore combines building's exergy management and manufacturing process analysis, and is illustrated by its application to three case studies of real manufacturing scenarios. A summary of major contributions to knowledge and the peer reviewed publications generated thus far from this research are also outlined. Finally, a chapter wise brief description of the thesis structure is provided to introduce the thesis concisely.

1.2. Background

Our planet is equipped with a finite amount of natural resources that are consumed in order to sustain human life. They can be broadly categorized into renewable (e.g. solar, wind) and non-renewable (e.g. coal, oil). In a report by the international energy agency (IEA, 2014), from 1971 to 2012, global energy consumption has continuously increased from 400 Mtoe (million tons of oil equivalents) to approximately 900 Mtoe. In addition to world energy use more than doubling, its rete of use shows an increasing trend. Furthermore, in a report by the U.S energy information administration (U.S. Energy Information Agency, 2013), it is estimated that the share of renewable supply in the world energy market was 11% in 2012, projected to reach 15% in 2040. It seems that at present and in the near future, the major portion (85% - 89%) of the resources used globally come from non-renewable sources i.e. fossil fuels.

In the (U.S. Energy Information Agency, 2013) report, projections of energy usage up to 2040 were made, see Figure 2. The OECD (Organisation for Economic Co-operation and Development) country's energy consumption is predicted to increase at a slow rate; however a sharp increase is predicted for the non-OECD countries. As evident from the world map in Figure 2, the non-OECD countries include, but not limited to, are large economics like China and India.

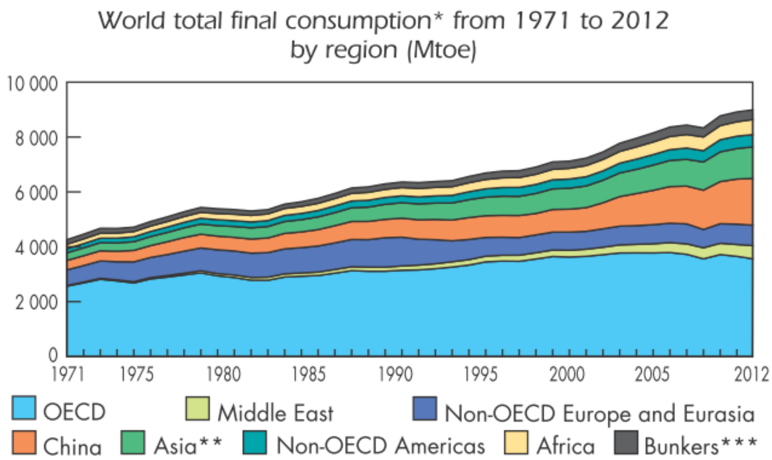

Figure 1 - Global energy consumption (IEA, 2014)

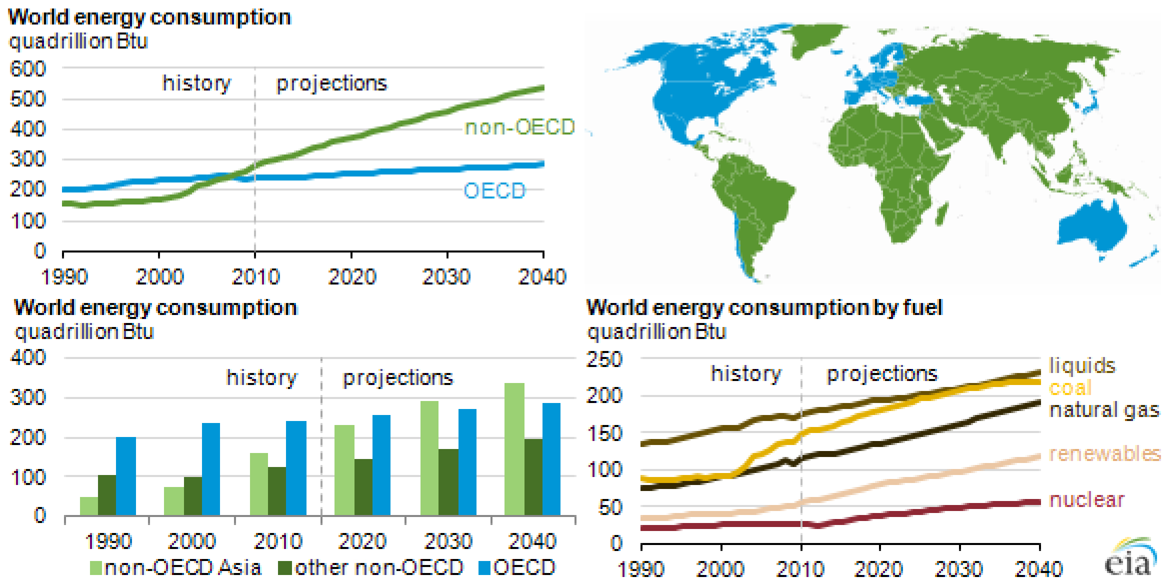

Figure 2 - Present and future projections of world energy consumption (U.S. Energy Information Agency, 2013)

According to a study by Singh and Singh (2012), the fuel reserves depletion times for oil, coal and gas are approximately 35, 107 and 37 years respectively. Therefore continuing with the current rates of consumption is not a sustainable option. Addressing this grave concern, the European Union designated resource efficiency as one of the seven flagship initiatives in its Europe 2020 strategy for smart, sustainable and inclusive growth (CEC, 2011). Following the strategy, the approaches and policies for resource efficiency of 31 EU and member countries were surveyed and summarized in the report by Kaźmierczyk (2012). In a similar report for the UK, Dawkins et al. (2010) outlined 13 broad measures for improved resource efficiency in the UK. The manufacturing sector is a significant consumer of resources, and is therefore the subject of this thesis. The next section provides some information regarding the share of resource use by manufacturing and thus highlights the importance of tackling the issue of industrial sustainability.

1.3. Resource consumption in the manufacturing sector

In the EIA (2013) report, the industry used more than half of the world's energy (51%) and it should be noted that agriculture was considered a part of this. Figure 3 below gives data on world energy use by each sector worldwide EIA (2013). As for manufacturing, the worldwide energy usage share from 2012 – 2040 has been projected to increase from 31% – 38%. Therefore, the issue of tackling industrial sustainability is an important one, and is attracting considerable attention from policy makers, practitioners and academics alike.

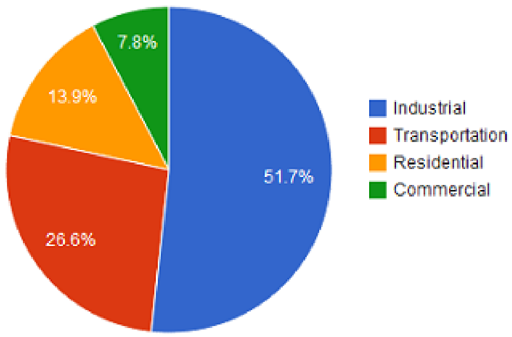

Figure 3 - International Energy usage by sector (EIA 2013)

The issue of sustainability is linked to resource consumption, which itself is not limited to energy only. Water efficiency also needs to be considered, and is predicted to gain more attention in the near future. At first glance, water is a plentiful resource; however it is not always available for human use in the quantity and quality required. As can be seen from Figure 4, most of the water present on the earth is saline, and is not suitable for human use if untreated. On the demand side, the industry was responsible for 19% of the global use, which cannot be neglected.

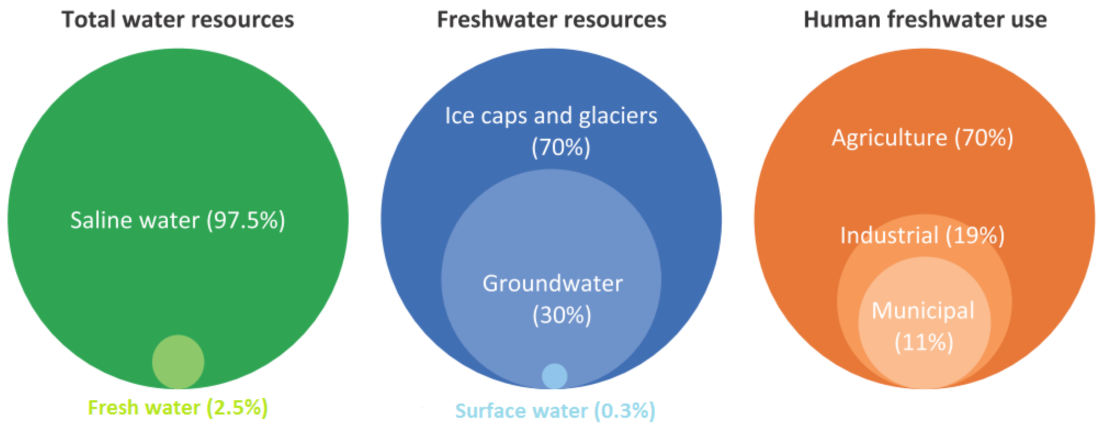

Figure 4 - Human fresh water availability and use IEA (2012)

A survey of the OECD countries predicts an increase in global water demand by 55% in 2050, with the share of manufacturing increasing by 400% (OECD, 2012). A report by the IEA (2012) further highlighted the importance of fresh water availability for the energy production industry, for which the water withdrawals in 2010 were 15% of the global total. More importantly, owing to increases in the efficiency of technology, the consumption of water by energy production was predicted to rise dramatically by 85% in 2035. These figures suggest that water efficiency in manufacturing should be considered an issue of importance at par with energy efficiency. The following section describes the general research focus, aims and objectives of this PhD project.

1.4. Research focus

The general area of research is sustainable manufacturing; therefore it becomes important to clarify what is meant by industrial sustainability. The word sustainability is a broad term and there are different interpretations of the concept. A definition of industrial sustainability that is pertinent to this research is as follows,

"A system that integrates product and process design issues with issues of manufacturing planning and control in such a manner as to identify, quantify, assess, and manage the flow of environmental waste with the goal of reducing and ultimately minimizing environmental impact while also trying to maximize resource efficiency."

(Melnyk and Smith, 1993)

From the definition state above and others similar, it appears that maximizing resource efficiency reduces environment impact. A similar view was taken by Gutowksi (2011) who reviewed the alternate meanings of sustainable manufacturing. Among these, resource accounting was identified as a method that has been widely used in scientific investigations of sustainability. Resource efficient manufacturing implies changing a manufacturing system to produce the same product using fewer natural resources. Therefore, resource accounting in manufacturing can help to conserve natural resources and thus promote industrial sustainability. For the remainder of the thesis, resource efficient manufacturing is considered to be directly linked to the sustainability of manufacturing systems.

1.5. Central aim

The research in the PhD project specifically investigates methods for measuring industrial sustainability, or resource accounting in manufacturing. The aim of the project is to advance the state of the art by presenting a more effective method for this purpose, the general research question is stated as follows,

The aim of this research is to develop a methodology that improves upon the state of the art in methods for measuring industrial sustainability.

1.6. Specific objectives

In order to achieve this central aim, the following objectives need to be met.

i. *Conduct a critical review of the state of the art in techniques for measuring industrial sustainability, in order to identify an area of improvement and a knowledge gap.*
ii. *Develop a methodology for measuring industrial sustainability that is generally applicable and overcomes the shortcomings identified in the literature review.*
iii. *To test the practical applicability of the approach on real factory environments.*
iv. *To test the robustness of the approach by applying it to different manufacturing environments.*
v. *Analyse the results in order to gauge the effectiveness of the devised approach (quantitative validation).*
vi. *If the approach is effective at measuring industrial sustainability, gauge its value for the industry (qualitative validation).*

The funding for this PhD research was provided through the (KAP) project which was an EU 7th Framework project under the 'Factory of the Future' programme (project number 260111). Therefore the broader goals of the PhD research were aligned with KAP. The mission statement of the KAP that aimed for resource efficiency in manufacturing was as follows,

> *The KAP research project aims to provide manufacturing standards to ensure that every existing resource can be used as efficiently as possible through the effective coordination of man, machine, material, and method.*

Additionally, the project partners at KAP presented an opportunity for access to case studies. The author was therefore involved with KAP, and conducted a case study on one of the partner's manufacturing facility, detailed in one of the subsequent chapters.

1.7. Summary of major contributions

1. A novel exergy based resource accounting methodology based on the concepts of industrial ecology has been developed. It uses an integrated model of the factory, where the building and production processes function as parts of a whole system.
2. The novel approach has been applied to an engine cylinder head production line, thus illustrating its practical applicability at the factory level.
3. The first exergy analysis of jaggery production was carried out in order to illustrate the application of the novel approach at industrial symbiosis level.
4. The first exergy analysis that focuses on modelling of water flows through a food processing facility has been carried out, to illustrate the potential application of the novel approach to varied manufacturing environments.
5. The value of the approach for industry has been gauged through qualitative feedback from practitioners and experts in the area.

1.8. List of related peer reviewed publications

Following is a list of publications that are derived from the author's original research work in this thesis and have not been submitted elsewhere except in the under listed journals and conferences.

1. Khattak, S.H., Greenough, R., Korolija, I. and Brown, N., 2016. An exergy based approach to resource accounting for factories. *Journal of Cleaner Production*, *121*, pp.99-108.
2. Khattak, S.H., Greenough, R., Sardeshpande, V and Brown, N., Resource efficient manufacturing: Can reduced efficiency lead to improved sustainability?, *In Industrial energy efficiency. Arnhem, Netherlands, 2014*. ECEEE. 163-170
3. Khattak, S.H., Greenough, R.,Korolija, I and Brown, N., Analysing the use of waste factory heat through exergy analysis, *In Industrial energy efficiency. Arnhem, Netherlands, 2014*. ECEEE. 179-190
4. Khattak, S.H., Greenough, R. and Brown, N., Suitability of exergy analysis for industrial energy efficiency, manufacturing and energy management, *In Industrial energy efficiency. Arnhem, Netherlands, 2012*. ECEEE. 237-245
5. Brown, N., Greenough, R., Vikhorev, K., & Khattak, S. (2012, June). Precursors to using energy data as a manufacturing process variable. In *Digital Ecosystems Technologies (DEST), 2012 6th IEEE International Conference on*(pp. 1-6). IEEE.

1.9. Thesis structure

While this introduction chapter provided an overview of the PhD research conducted, the remainder of the thesis presents it. In Chapter 2, the literature relevant to the topic of this research is reviewed. It provides information about conventional methods used for measuring sustainability in manufacturing and the state of the art in this subject area. The method chosen for this research is exergy analysis; therefore its application in various relevant contexts is reviewed in detail. In addition, the case study chapters that follow provide additional review that is necessary for the case at hand.

Chapter 3 describes the research methodology used, the aim of which is to address the objectives outlined in section 1.4.

Based on the literature review, a specific knowledge gap was identified. Chapter 4 addresses the gap by presenting a novel approach for measuring resource efficiency in manufacturing, which is also a conceptual model for improving industrial sustainability. The three chapters that follow illustrate the application of the approach in practice to real manufacturing scenarios.

Chapter 5 presents a case study of an engine cylinder head manufacturing line, which illustrates the application of the novel approach previously presented in Chapter 4.

Chapter 6 provides a case study of a jaggery making process, the aim of which is to illustrate the use of the approach for industrial symbiosis.

Chapter 7 is a case study of a food manufacturing facility, the aim of which is to illustrate the application of the approach in differing manufacturing scenarios. Specifically, the impact on resource use by the factory due to water reuse is quantified. While Chapters 5 - 7 provided quantitative validation and its effectiveness of quantifying resource use, Chapter 8 addresses the question, “is the approach of value to the industry?” The results from interviews and questionnaires are presented in an attempt to answer this question.

Chapter 9 presents a discussion on the PhD research pertaining to the contributions to knowledge, its limitations and possible future research directions.

Chapter 2 Literature review

2.1. Chapter overview

The introduction to the thesis highlights the problem of declining fossil fuel reserves and the unsustainable trend of consumption in a global context. Manufacturing is responsible for a significant portion of this consumption; therefore reducing it becomes an issue of importance on a global scale. Also, it is evident from the results of reports presented in sections 1.1 and 1.3 , that reduction of industrial resource consumption is an issue that is attracting attention both at the UK and the EU level. In this background, analysis methods that can help identify inefficiencies in manufacturing systems, may lead to a reduction in the consumption of resources. This chapter presents a review of relevant literature to methods and ideas that promote energy efficiency and sustainability in the industry, to identify a knowledge gap that the research will seek to fill.

The approach to reviewing literature is central to conducting a thorough review and shapes the direction of future research. The approach taken in this research project is described in section 2.2, followed by a brief introduction into the related methods used for measuring industrial sustainability. A common drawback in the conventionally used methods is identified which leads into the concept of exergy. The 2nd law of thermodynamics based quantity exergy, is introduced in detail for readers new to this concept. The application of exergy analysis to environmental science in general and manufacturing specifically, are discussed in sections 2.6 and 2.8 respectively. Section 2.9 discusses the need to consider the factory as a whole system, comprised of the processes and the building. The review culminates in a refined research question that is based on the specific knowledge gap identified.

2.2. Approach to literature review

The exploration of literature started from a general research area which lead to the identification of a specific knowledge gap (Figure 5). Initially, keywords such as “efficient manufacturing”, “sustainable manufacturing”, “energy efficient manufacturing”, “green manufacturing”, “optimized manufacturing” etc. were used to specify a narrower area of research. In addition to keywords, following the works of pioneers and prominent researchers in the area was particularly useful in finding related literature. In such an interdisciplinary field, a large body of literature was reviewed from which two areas of interest were identified;

(i) Analysis methodologies for improved efficiency in manufacturing.

(ii) Condition based monitoring with fault diagnosis for improved efficiency in manufacturing.

Based on further exploration of literature, the former topic was selected for further exploration. Additionally, the objectives of researching analysis methodologies aligned well with the goals of the KAP project (KAP) from which data for case studies could be acquired.

Predominantly, thermodynamics based approaches were found to be used for measuring efficiency in manufacturing. The methods based on thermodynamics can be broadly classified into 1st and 2nd law based techniques, and were researched using keywords such as “energy analysis”, “material flow analysis”, “2nd law analysis”, “exergy analysis”, “ entropy analysis”, “emergy analysis” etc. These keywords were used in conjunction with the general research area in order to search through a large body of articles. Sources included books, journal articles, conference papers, and academic websites with a greater focus on journal articles. Academic search engines such as “Google Scholar”, “Scopus”, “Science direct” and “Web of Knowledge” etc. were used to search for literature using the keywords mentioned. The next section provides an introduction to the conventional analysis methods used for measuring efficiency in manufacturing.

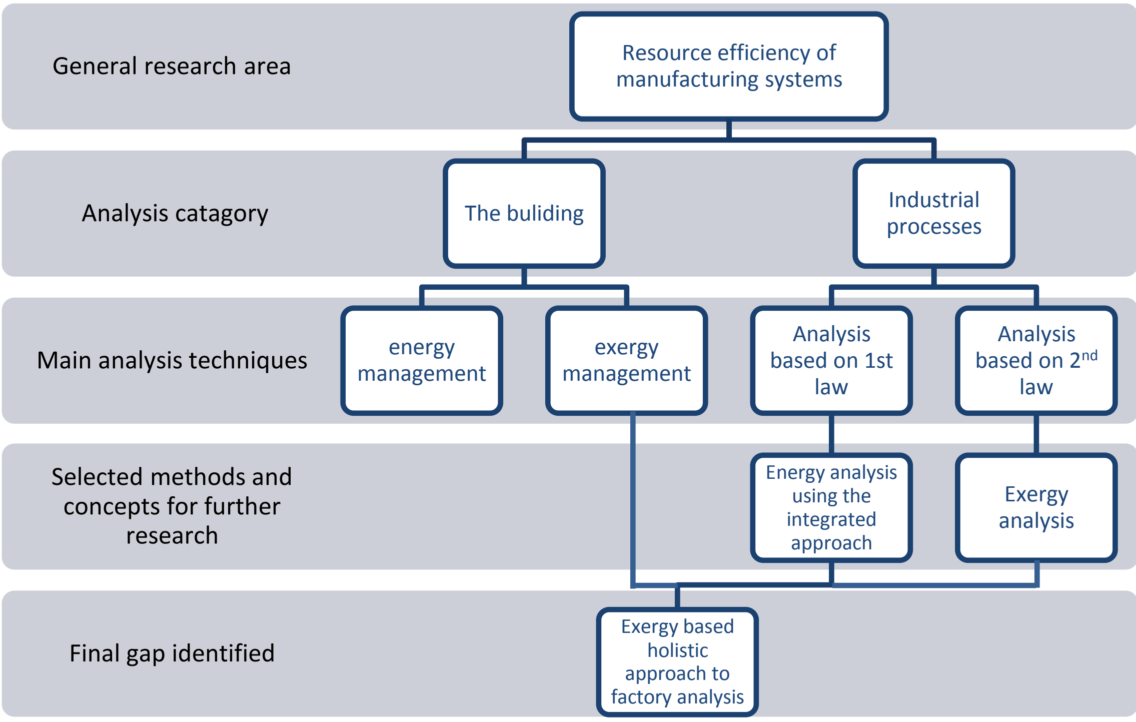

Figure 5 - Literature review structure

2.3. Conventional methods for measuring industrial sustainability

Sustainability in manufacturing is primarily pursued using strategies that improve energy and material efficiency of the system. Since both the material and energy demand of a factory constitutes its total resource usage, a reduction in resource demand impacts the sustainability of a factory directly. Industrial energy management is a means to improving energy efficiency and has been defined by Hasanbeigi and Price (2010) as,

"The strategy of adjusting and optimizing energy, using systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing total costs of producing the output from these systems "

In order to implement energy management, an energy audit has to be carried out. The energy audit is a systematic approach which enables the energy auditor to identify waste energy opportunities and implement efficiency measures. It is conducted in chronological steps which are well defined in such standards as the "European standard on energy efficiency", BS EN16247 (Imrit, 2013). The energy audit process can be explained in a simplified manner in three short steps.

- First is the initial walk through audit which is a qualitative exercise. It enables the auditor to understand the facility, meet key personnel and suggest improvement measures that are apparent.
- The second step involves data gathering and analysis. This is a more detailed analysis of the facility in which the material and energy flows are identified, and the mass and energy balances for the process/building are set up. Based on this quantitative analysis, energy conservation opportunities are identified. These opportunities are assessed economically and the whole study is presented to the managers of the facility.
- The final step is the implementation, which is followed up by periodic reviews to maintain the efficiency of the facility.

In the energy audit methodology, energy analysis is a key part of the optimization process. A summary of the conventional energy analysis methodologies can be found in an article by Brown et al. (2014), in which a useful approach to organising and communication of the various energy analysis techniques was presented.

With regards to the second source of resource consumption in a factory, the materials supplied, Rashid et al.(2008) identified four major strategies for improving material efficiency. These are waste minimisation, material efficiency, resource efficiency and eco-efficiency.

Waste minimisation is described as the reduction of waste at the source, therefore reducing waste production rather than treating it afterwards. Material efficiency can be defined as the ratio of the output of products to inputs of raw materials. It is simply an efficiency metric that is exclusive for material flows, and can be used as part of a larger strategy. The third major strategy, resource efficiency, is designed to reduce the consumption of resources drawn from nature and has also been defined by Dahlström and Ekins (2005) simply as a combination of material and energy efficiencies. Finally, eco-efficiency is a broader term that incorporates effects of human welfare and environmental pollution, and is commonly defined as follows (Dahlstrom and Ekins, 2005) ,

$$The\ eco-efficiency\ of\ production = Profits\ generated\ /\ Pollution\ produced$$

Rashid et al.(2008)compared the four strategies based on the clearness of definition, scope of application, practicality and compatibility (Figure 6). The comparison showed that waste minimisation is well-defined, easy to implement but limited in scope. In contrast, eco-efficiency is a broad concept but is difficult to implement in practice.

Characteristic	Strategies	Waste Minimisation	Material Efficiency	Resource Efficiency	Eco-Efficiency
Definition	Type	Concrete - *1,2*	Concrete	Concrete	Philosophical -*3,4,5*
	Orientation	Goal oriented	Action oriented	Action oriented - *9*	Measurement oriented
	Focus	Effect-waste -*1*	Cause- material	Cause- resources	Cause/effect – Resources/pollution
	Main goal	Reduce waste and pollution Reduce cost-*1,6*	Efficient use of resources (both material and energy) Reduce waste and pollution -*7*	Efficient use of resources Reduce waste and pollution	Efficient use of resources, Reduce waste and pollution, Quality of life Earth carrying capacity - *8*
Scope	Systems Boundaries	Limited -downstream	Upstream-downstream -*7*	1)Do not cover upstream and downstream activities -*9* 2) Cover upstream and down stream by measuring MIPS - *10*	Claimed to cover upstream-downstream by addressing all stages of product life-cycle -*11* - but seen as debateable- *12*
	Influence over Externalities	Limited	Yes	Yes	Yes - supposedly big influence
	Level usually used	Process, Company and National	Process, Product-*7*	Product, Company and National-*13*	Product ,Company and National *3,4,5*
	Depth of issues to be tackled to achieve goal	Relatively easy	Potentially difficult	Difficult	Very difficult -*3*
	Concerns (e.g economy, ecology, social)	Limited	Limited -*14*	Broad	Broad -*3,4,5*
	Utility being assessed	Weight, volume, cost	Functionality/services	Unit of value added	Unit of value added - *8,15*
Practicality	Measurement and Target	Direct/simple - *1,16* Quantitative - *1,6*	Potentially complicated Quantitative	Complicated Quantitative - *17*	Complicated -*3* Quantitative *17* and Qualitative
	Indicator Effectiveness	Yes	Potentially difficult	Difficult	Very Difficult - *20*
	Technical Feasibility	Yes	Potentially difficult	Difficult- *17,18,19,20,21*	Difficult
	Data Availability	Easy - *1*	Potentially yes	Difficult	Difficult
	Easy of Communication	Yes	Potentially yes	Potentially yes	Difficult
	Does it guide actions	Yes	Potentially yes	Potentially yes	Debateable- *3,4,20,22,23*
Compatibility	between goal and measurement	Yes	Potentially yes	Potentially yes	No – difficult to determine on earth's carrying capacity- *3*

Authors:
(1) Bates & Philips, 1998 (2) Clelland et al, 2000 (3) Ehrenfeld, 2005 (4) McDonough & Braungart, 1998 (5) Honkasolo, 2001 (6) Cheeseman & Philips, 2001 (7) Worrel, 1997 (8) WBCSD, 2000a (9) Commission of European Communities, 2003 (10)Schmidt-Bleek, 1995 (11) Mosovsky et al, 2000 (12) Warhurst, 2002 (13) Cramer & van Lochem, 2001 (14)Worrell, 1994 (15) OECD, 1997 (16)Hanssen et al, 2003 (17) Reijnders, 1998 (18) Hawkins & Shaw, 2004 (19)Pearce, 2001 (20)Foxon, 2000 (21) Figge & Hahn, 2004 (22)Huesemann, 2004 (23)Jansen, 2003

Figure 6 - Comparison of strategies for reducing industrial material consumption (Rashid et al., 2008)

All the concepts, methods and metrics described thus far are useful for benefiting industrial sustainability. However, the approaches mentioned, are based on the 1st law of thermodynamics and suffer from a common limitation. The 1st law of thermodynamics is stated as, *When a system undergoes a thermodynamic cycle then the net heat supplied to the system from its surroundings plus the net-work input to the system from its surroundings is zero.*

(Eastop and Mc Conkey, 1986)

Simply explained in the context of industrial resource efficiency; mass and energy are conserved quantities that can be used to model all flows through a manufacturing system. Frequently, resource consumption is quantified using the 1st law, however quantifying the consumption of resources based on naturally conserved quantities can be limiting and may lead to misleading results. Even though energy is conserved through its various transformations, it loses its 'value' along the way. The link between 'value' and costs have led to the development of cost benefit analysis (CBA) techniques which are used for environmental appraisals. However, as argued by Hammond and Winnet (2006), the process of valuation is uncertain and potentially controversial. The article highlights that environmental concerns are long term issues and predicting long terms prices based on short term trends make CBA techniques along inadequate for resource accounting. The quantity exergy; based on the 2nd law of thermodynamics is consumable and takes into account the quantity as well as the quality of mass and energy flows. The subsequent four sections provide a detailed introduction into the concept of exergy, its strengths and limitations, followed by an in-depth review of its application to environmental science in general and manufacturing in specific.

2.4. Analysis methods based on the 2nd law of thermodynamics

All real world systems are subject to the 2nd law of thermodynamics that has been expressed in different ways, one of which is stated below,

"It is impossible for a heat engine to produce a net work output in a complete cycle if it exchanges heat only with a single energy reservoir"

(Eastop and Mc Conkey, 1986)

A general schematic of a heat engine is depicted in Figure 7 which is actually a graphical representation of the 2nd law. A heat engine is a device that uses heat from a high temperature source to produce work while rejecting a portion of the heat supplied to a lower temperature sink. The 2nd law stated above dictates that the heat engine must have a lower temperature reservoir. In other words, some of the supplied heat must be lost to a lower temperature sink which leads to the Kelvin-Plank statement,

"It is impossible to convert heat completely into work"

In addition to the constraint of heat rejection to a low temperature reservoir, Figure 7 also shows that heat shall always flow naturally from high to a lower temperature, therefore the 2nd law associates a direction to all natural processes. If heat were to be delivered in the opposite direction, then energy from an external source would be required. This leads to another version of the 2nd law stated as follows,

"It is impossible to construct a device that operating in a cycle will produce no effect other than the transfer of heat from a cooler to a hotter body"

(Eastop and Mc Conkey, 1986)

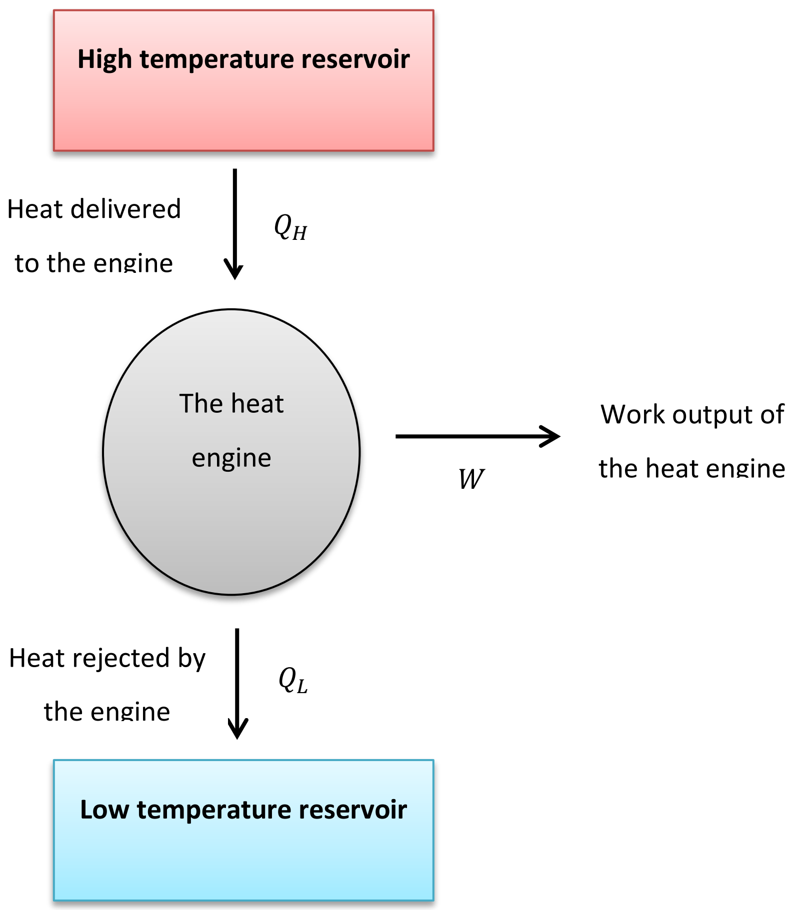

Figure 7 - The heat engine schematic

From the statements of the 2nd law and the brief explanation, it is clear that work can only be extracted from heat that is of a higher temperature as compared to the sink. As the heat naturally flows through the system (in this case, the heat engine); its temperature drops therefore losing its useful work potential. The loss of work potential or value can be thought of as degradation in quality in the heat flow stream. Hence, an energy stream not only has quantity but also quality. The work potential of an energy stream is quantified through the thermodynamic state variables, entropy, exergy and entransy. Entropy and exergy are direct consequences of the 2nd law while entransy relies on an analogy with electrical systems. Since analysis methods can be based on either of the three quantitates, each one is briefly introduced. Exergy is explained in greater detail as exergy analysis was chosen as the method of analysis in this research.

2.4.1. Entransy:

Entransy, a recently defined physical quantity by Guo et al. (2007), has been used as a basis for optimising heat transfer systems. It is based on an analogy between thermal and electrical systems and corresponds to the electrical energy stored in a capacitor. The analogy is seen in Figure 8, where the equivalent of electrical potential energy stored in a capacitor seems to be missing.

Electrical charge stored in capacitor Q_{ve} [C]	Electrical current (charge flux) I [C]/[s] = [A]	Electrical resistance R_e [Ω]	Capacitance $C_e = Q_{ve}/U_e$ [F]
Heat stored in a body $Q_{vh} = Mc_v T$ [J]	Heat flow $\dot{Q}_h$ [J/s]	Thermal resistance R_h [s K/J]	Heat capacity $C_h = Q_{vh}/T$ [J/K]
Electrical potential U_e [V]	Electrical current density $\dot{q}_e$ [C/m^2 s]	Ohm's law $\dot{q}_e = -K_e \frac{dU_e}{dn}$	Electrical potential energy in a capacitor $E_e = \frac{1}{2} Q_e U_e$ [J]
Thermal potential (temperature) $U_h = T$ [K]	Heat flux density $\dot{q}_h$ [J/m^2 s]	Fourier law $\dot{q}_h = -K_h \frac{dU_h}{dn}$	?

Figure 8 - Analogies between electrical and thermal parameters (Guo et al., 2007)

It follows from the analogy that entransy, $\overline{G}$, be defined as,

$$\overline{G} = \frac{1}{2} UT$$

Where *U* is the internal energy and *T* is the temperature of the system. Even though Guo et al. (2007) defined the extremum conditions of entransy dissipation for heat transfer systems optimisation, the concept suffers from certain drawbacks. A major limitation as identified in a review article by Sekulic et al. (2015) is that entransy is defined only to be applicable to systems that do not involve heat – work conversions. This limits the application to a rather narrow area, and is perhaps its biggest drawback in the context of manufacturing systems. It is hard to imagine a manufacturing system without heat – work conversions, thus leading to the exclusion of using the property entransy. Even if a specific process were to be considered that does not have heat – work conversions (for e.g. a heat exchanger), it is likely to be affected by other heat – work conversions that form the manufacturing environment.

2.4.2. Entropy:

Entropy, S, is the measure of disorder of a system and defined mathematically as,

$$\Delta S = \frac{\Delta Q}{T}$$

Entropy can also be thought of as the part of an energy stream which is unavailable to do work. As natural systems proceed through time, entropy is always generated due to inherent irreversibilities in the system and a greater part of the energy stream is unavailable to do work. Therefore, it is an indicator to loss of value or quality as an energy stream flows through its various transformations. Consequently, entropy generation minimisation has been commonly used as a criterion for optimising heat transfer cases in diverse systems (Chen et al., 2011). While entropy generation can certainly be used to quantify the loss of value in resources, the exergy concept is better suited to application in manufacturing environments. Sections 2.5 - 2.8 introduce the concept of exergy, describe its application to environmental science, and then finally its application for manufacturing.

2.5. Exergy:

The discussion in the previous section (2.4) shows that energy has quality as well as quantity. While the quantity of energy remains conserved through the various transformations, its quality is degraded due to thermodynamic irreversibilities. Exergy, a property of physical systems based on the 2nd law, takes into account the effect of irreversibilities and can be used to model energy as well as mass flows.

The exergy of a thermodynamic system is defined as “The maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only” (Tsatsaronis, 2007). It is a property of both the system and the environment when both are considered as part of a composite system (Bakshi et al., 2011). When a mass or energy stream reaches equilibrium, it does not have the ability to impact the surroundings. Exergy represents the variation of a mass or energy flow from the equilibrium state which is effectively a representation of its useful work potential.

Therefore, exergy can be used to model mass and energy flows of varying quality levels in common units while quantifying their useful potential. As the various resource flows pass through the manufacturing environment, they are consumed at their respective transformations. This gives exergy analysis an advantage over 1st law techniques for the purpose of quantifying natural resource consumption. A classification of different types of exergy has been given by Gundersen (2009) and is depicted in Figure 9.

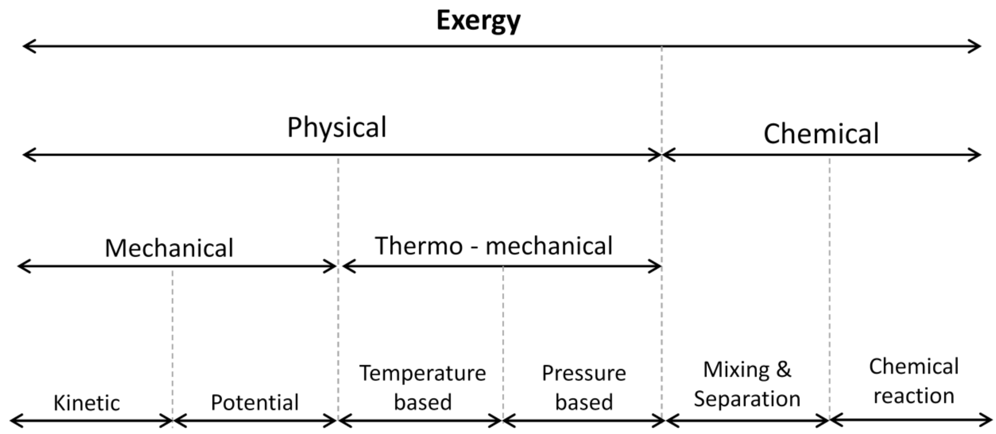

Figure 9 - Classification of the forms of exergy (Gundersen, 2009)

What follows now is the mathematical derivation of exergy based on the 1st and 2nd law of thermodynamics, followed by a description and the equations that can be used to calculate the forms of exergy shown in Figure 9. A mathematical derivation of the property exergy, which uses the 1st and 2nd law of thermodynamics, is provided in Appendix 1 of this thesis. For more practical purposes, the following equation describes the total exergy of a mass flow,

$$Ex_{total} = Ex_{thermo-mechanical} + \underbrace{Ex_{formation} + Ex_{concentration}}_{Ex_{Chemical}} + Ex_{kinetic} + Ex_{potential}$$

Each term in this equation is now described along with the mathematical expressions that could be used to calculate the respective exergy form.

$\boldsymbol{Ex_{thermo-mechanical}}$:

The thermo-mechanical exergy component is due to the temperature and pressure of mass flow. The thermal exergy component is calculated using the difference in temperature of the mass flow and the reference environment. The mechanical exergy component is calculated using the specific volume and the pressure differential that exists between the mass flow and the reference environment. For incompressible substances and ideal gases, this exergy component is calculated using equation as follows,

$$\boldsymbol{Ex_{thermo-mechanical} = mc_p\left[T - T_0 - T_0 \ln\left(\frac{T}{T_0}\right)\right] + V(P - P_0)}$$

For steam, a substance commonly used on physical processes, the steam tables can be used to look up values of the required properties.

$Ex_{kinetic}$& $Ex_{potential}$:

Since kinetic and potential energy represent work potential, they are calculated exactly similar to kinetic and potential energy. The kinetic exergy is calculated using the absolute velocity of the mass flow while potential exergy, similar to potential energy depends on the height from a reference. Both these exergy components can be calculated using the following equation.

$$Ex_{kinetic} + Ex_{potential} = \frac{1}{2}m\left(\vec{V}^2 - \vec{V}_0^2\right) + mg(z - z_0)$$

Where $\vec{V}$ is the velocity [m/s], *z* is the height, *m* is the mass and the subscript zero represents the quantity at the reference.

$Ex_{Chemical}$:

The chemical exergy is composed of two parts, the chemical formation exergy (due to chemical reaction (Figure 9)) and the chemical concentration exergy (due to mixing and separation (Figure 9)).

For substances that are not present in the reference environment, a general reversible chemical reaction is assumed that establishes its formation using the elements present in the reference environment. For a general reversible chemical reaction,

$$xA + yB \ \leftrightarrow zL$$

Where *A, B* and *L* are the reactants and products, and *x, y, z* represent the moles of its corresponding substance based on the stoichiometric balanced chemical reaction. Then, the chemical formation exergy is calculated as follows (Tai et al., 1986),

$$ex_{formation} = \Delta G^0 + RT_0 \ln[\frac{L^z}{A^x B^y}]$$

Where, ΔG^0 is the Gibb's free energy at standard conditions, and is tabulated in easily available thermodynamic property tables such as Lide (2007). Also, *R* is the universal gas constant (8.314 J/kgK) and T_0 is the reference environment temperature (298.15K). The standard chemical exergies of elements and common compounds has been tabulated by Szargut et al. (2005a) and can also be found in online databases such as the exergy ecology online portal (CIRCE, 2008).

For substances that already present in the reference environment, the difference in the concentration in the mass sample and in comparison with its concentration at reference environment conditions represents a theoretical work potential and is termed as the concentration exergy. Concentrations of various chemical substances that are commonly present in the RE along with the standard chemical exergy values were calculated by Szargut et al. (2005a), which have been updated by Rivero and Garfias (2006) and is given by,

$$Ex_{concentration} = mRT_0 \sum_k x_k \ln\left(\frac{C_k}{C_0}\right)$$

Where C is the concentration, x is the mole fraction, k is the number of substances within the mass with their respective concentrations and the subscript "o" indicates that the property is at the reference environment condition.

If the substances involved in the analysis are present in the chemical exergy tables (Szargut et al., 2005a), then chemical exergy calculation is fairly straight forward. If they are not present in the tables, then the above presented methodology has to be used. Chapter 7 presents a case study with such a scenario in which further detail for chemical exergy calculation is given.

While the exergy associated with a mass flow is described above, energy interaction can also be modelled in terms of exergy. For work flows, e.g. electricity, they are equal to exergy as by definition, exergy is the maximum work obtainable and can be written as,

$$\Delta Ex_{work} = \Delta W$$

For heat flows, Figure 10 depicts the variation of energy quality with temperature and is mathematically written as,

$$Ex_{heat\ flow} = Q(1 - \frac{T_0}{T})$$

This equation can be understood as the work obtainable from a heat flow through the Carnot engine. Since the Carnot engine assumes reversible conditions, the Carnot factor multiplied with the heat flow represents the maximum work obtainable from the heat flow. Figure 10 shows the trend of exergy in relation to temperature of a heat flow (in Celsius). It is clear that at reference temperature (25^{o}C), the exergy is zero and increases with an increase in variation from the reference. It is interesting to note that the increase is considerably sharper as the temperature goes below the 25^{o}C as compared to when it rises above it. It is important to note here that 25 Celsius was taken as the reference in this case, and a change in selection of the reference environment conditions will affect the exergy content accordingly.

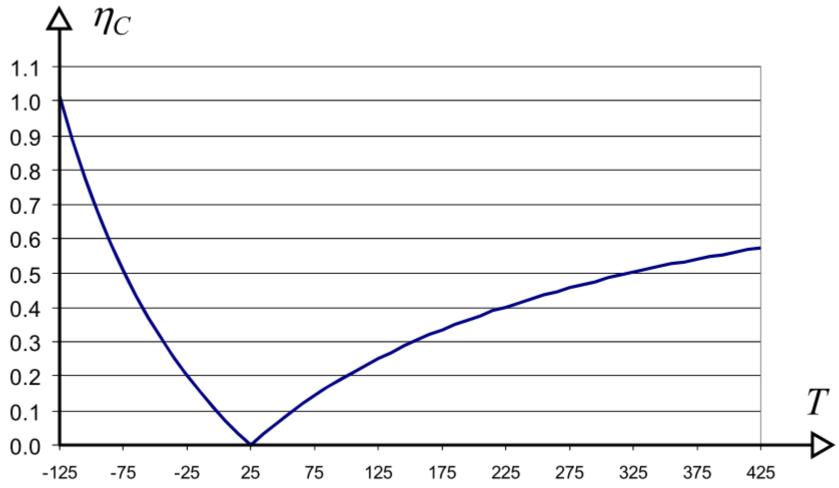

Figure 10 - The Carnot factor as a function of temperature in Celsius (Gundersen, 2009)

While Figure 10 is suitable for quantifying the exergy of heat flow through conduction and convection, it cannot be applied when radiation is the main mode of heat transfer. The maximum work obtainable from radiation energy has been the subject of interest in many research papers in the last four decades. Candau (2003) points out that the exergy of a radiation flow is a debatable issue, however the formulation based on classical thermodynamics is generally accepted and is given as follows,

$$Ex_{rad} = Q_{rad}\left(1 - \frac{4}{3}\frac{T_0}{T} + \frac{1}{3}\left\{\frac{T_0}{T}\right\}^4\right)$$

2.5.1. Limitations of the exergy concept:

Exergy is a property of both the system and the environment; therefore the definition of not only the system but the 'exergy environment' is cardinal to the theoretical formulation of the exergy concept. The problems associated with its theoretical robustness have been outlined in detail by Gaudreau et al. (2009) and are now discussed.

First of all, the theoretical formulation required for the derivation of exergy can be problematic. In the derivation of non-flow exergy, the fundamental requirements necessary to quantify exergy are inherently in conflict. The basic problem lies in the fact that the natural eco-system environment and the exergy reference environment by their basic descriptions have features completely opposing one another, thus assuming one to be an analogue of the other would be wrong. For example, the thermodynamic environment is in stable equilibrium in which its intensive states i.e. temperature, pressure and chemical potential of its substances remain unchanged. The natural environment however is not in stable equilibrium, is in a state of constant flux consisting of sub systems. Clearly, these two are the opposite of one another but they are taken to be the same for exergy calculations.

Secondly, exergy is considered to be the measure of resource value on the basis of the departure of the state of a resource from its equilibrium state (Ayres et al., 1998). On the other hand, toxic waste flows are also at a variation from the equilibrium state, thus having positive values of exergy that indicate useful work potential. This is not representative of reality and therefore exposes this limitation i.e. exergy does not differentiate between waste and resource flows. Some researchers have tried to address this issue by characterising resource exergy as restricted and of waste as unrestricted (Ao et al., 2008). However, this reasoning also has a flaw since flows such as sunlight, water and wind are all unconstrained yet useful resource streams. Furthermore, exergy does not quantify accurately the value of non – work producing materials, a simple example being of minerals. Valero (2006) has compared the theoretical chemical exergy value of a mineral resource to the empirical work required to refine the minerals from a mixture to pure states (Gaudreau et al., 2009). The correlation between the theoretical and empirical values was weak and this exposed a further limitation in using exergy for modelling non-work producing substances.

The application of the exergy concept can also be problematic, for instance the issue of a robust exergy efficiency definition for manufacturing was highlighted by Kellens et al. (2011a). The various definitions of exergy were compared by applying them to subtractive, additive and mass conserving manufacturing processes. The results suggest that no definition is robust enough to be applied to all three types of manufacturing processes. Additionally, since energy saving is not the main goal of a manufacturing process, an exergy analysis may be considered superfluous to what is necessary. Furthermore, in order to carry out an exergy analysis over the production cycle of a manufacturing process, some necessary thermodynamic assumptions need to be made in order to simplify the analysis. A critical one is assuming the process to be a steady state, but if this assumption affects the accuracy of the analysis considerably, then it makes conducting the exergy analysis much more complicated and thus it questions the practical utility of such a technique. In comparison with an energy analysis, additional data requirements of the exergy analysis method may also hamper its practical usage. Therefore, if exergy analysis has to be used for manufacturing systems, it must be clearly defined, careful assumptions must simplify the methodology and the benefits that are to be achieved by it must outweigh the effort required to conduct it.

The exergy concept has been used to explain the most probable behaviour of complex natural systems, but the theories that have arisen from it are still heavily debated (Dewulf et al., 2008). A combination of exergy and economic concepts, leading to the terminology, ‘thermoeconomics’ has been used for fault diagnosis in energy intensive systems (Antonio Valero et al., 2010). Valero et al. (2004) introduced the structural theory and malfunction/fuel impact formula for purpose. However it was highly criticized in the study by Kelly et al. (2008) in which structural theory approach was compared with the three other approaches for a simple gas turbine system. The results from the structural approach varied significantly from the other three approaches which suggested erroneous values produced by structural theory methodology.

Since, exergy depends on the reference environment as well as the systems; the changing environment can have an effect on the values generated. Rian (2011) conducted exergy analysis for three systems with a variation in the environmental temperature and humidity: A regenerative steam injection gas turbine (RSTIG), a simple Linde air liquefaction gas plant (Air-Liq), and an air-source heat pump water heater (HPWH).The results showed the impact of considering the variations in temperature and humidity of the reference environment. The impact of the reference environment was critical for HPWH thus proving that changes in the reference environment cannot always be ignored. Additionally, chemical exergy is highly dependent upon the selection of the reference species in the reference environment. A detailed discussion about the effect of reference environment elements selection upon chemical exergy calculations is presented in chapter 7.

Finally, a direct relationship between increasing resource efficiency of factories and industrial sustainability cannot always be assumed. Even though it seems logical to think that consuming fewer resources to produce the same products will lead a reduction in global resource consumption, but history suggests otherwise. An overview of the historical effectiveness of efficiency improvements in reducing mankind's resource consumption was conducted by Dahmus and Gutowski (2011). In the study, history shows a 'rebound effect' in which improvements in resource efficiency have generally not reduced mankind's overall consumption of resources. An increase in efficiency tends to reduce cost which in turn increases demand. For this reason resource efficient manufacturing cannot be considered in a straight forward manner, synonymous with industrial sustainability.

Although exergy analysis may be a useful tool for increasing the resource efficiency, it is perhaps a part of the full toolkit for industrial sustainable development (Hammond, 2004). It is therefore necessary to realize that it cannot be used as the sole measure for sustainable activity and should be used in conjunction with other techniques to acquire a realistic an accurate measure of sustainability (Hellström, 1997). Nonetheless, it has many advantages compared to 1st law based techniques which are detailed in the following section .

2.5.2. Strengths of the exergy concept:

As discussed in sections 2.3 and 2.4, energy efficiency is the most common tool currently used for measuring the 'effectiveness' of a process. Unfortunately, a focus on energy efficiency alone can mislead the analyst which can result in poor design decisions (Rosen, 2007). This can be illustrated when the energy and exergy efficiencies for various electrical devices are calculated and compared.

According to Granovskii et al.(2008a), exergy efficiency can pinpoint the inefficiencies in a better way by identifying and quantifying the types, causes and locations of the losses as compared to energy efficiency. There are many examples in literature reinforcing this point; just a few in varied fields of application are presented in articles by Petela (2008), Mert et al. (2012), Chen et al. (2009) and Gutiérrez and Vandecasteele (2011). A simple one is an example of an electric resistance space heater. The energy efficiency of such a device is usually near 100% but the exergy efficiency is less than 10%(Rosen, 2007). The reason is that the highest quality energy supply, electricity (work), is used to provide a very low quality energy demand i.e. low grade heat. The same heating could be accomplished by a heat pump which would increase the exergy efficiency of the process threefold. The concept here is to improve the exergy efficiency of the heating system, by using lower quality input energy where possible.

An example of a more complex physical system is that of a coal power plant as presented in the article by (Rosen, 2007). The overall energy efficiency for the power plant was 37% as compared to the exergy efficiency of 36%. The overall efficiencies suggest that both the energy and exergy approaches produce similar results, however a deeper investigation revealed otherwise. Energy identified the steam generators of the power plant to be 95% efficient whereas their exergy efficiency was 50%. This means that although most of the energy that is supplied to the steam generator ends up in the steam produced, the quality of the supply energy degrades through this energy transformation. When the condenser part of the power plant was analysed, the energy approach identified it as the major cause of losses, however the energy that entered the condenser was of low quality and therefore possessed low exergy. Therefore, the exergy approach did not identify the condenser to be the major cause of thermodynamic loss to the power plant. In summary, the energy approach identified the condenser as the main source of loss whereas the exergy approach assigned the greatest losses to the steam generator. Therefore, in order to improve the resource efficiency of the power plant, conventional energy analysis would focus attention towards the condensers, even though the more significant loss of useful work potential (or value) was occurring in the steam generators. This example along with others identified in the article by (Rosen, 2007), suggest that exergy analysis is better at locating thermodynamic losses in complex systems. This is basically due to fact that energy has both quantity and quality aspects, and exergy analysis takes into account both of these facets of energy, thus providing a more complete analysis as compared to 1^{st} law based approaches.

Entropy analysis is a method that also takes into account the energy quality but is expressed in the rather obscure units of Joules per degree change in temperature. On the other hand exergy is expressed in energy units therefore making it easier to understand. Additionally, exergy can be used to model energy as well as mass flows, thus making it suitable for application to manufacturing environments. Finally, quantifying resource consumption using 1^{st} law based conserved (non-consumable) quantities can be misleading. However, exergy can be consumed and can therefore act as a suitable indicator of resource consumption.

Summarising, exergy is a consumable quantity that can be used to model mass and energy flows which also takes into account the quality as well as quantity of mass and energy flows. Despite its limitations as detailed in section 2.5, it has benefits over 1^{st} law methodologies that make it a suitable concept for measuring industrial sustainability. Exergy analysis is a flexible tool which has been applied to sustainability study, economics, ecology, policy making, ecosystem analysis and even societal systems. Section 2.6 details the application of exergy to these areas of study, while section 2.8 presents its application specifically to manufacturing.

2.6. Application of exergy to environmental science

Based on the link between exergy and value of resource flows, the application of exergy to environmental science in general will be reviewed in this section. Such reviews have been previously presented, for example, Sciubba and Wall (2010) recorded the applications of exergy analysis starting from its early beginnings up to 2004. While the article was extensive at documenting the use of exergy, some areas such as physical hydronomics (Valero et al., 2009a) and building's exergy management (Schmidt, 2004) were not mentioned. More recently review articles have been written by Bonamini (2013), Tadese and Tesema (2014) and Romero and Linares (2014). While these articles reviewed literature relevant to their research, and provided the applications of exergy in environmental science, they did not cover a number of areas outlined by Sciubba and Wall (2010). This section presents a general overview of the applications of exergy analysis to environmental science, with the objective of adding to the previously conducted reviews by covering buildings exergy management and physical hydronomics. Therefore, sections 2.6 - 2.9 aim to provide a review of the state of the art relevant to sustainable manufacturing.

2.6.1. Ecosystems modelling

Since exergy can be used to model all types of resource flows, it has been used to model the natural resource wealth of the earth. Using exergy as a basis, Hermann (2006) modelled the flow of natural resources on a global scale. Figure 11 is a pictorial representation of this where primary natural resource reservoirs supply exergy to the biosphere along with the illustration of the consumptions of exergy in the various stages of transformations. Consequently, the path of exergy through the terrestrial system from input to its eventual natural or anthropogenic destruction is presented.

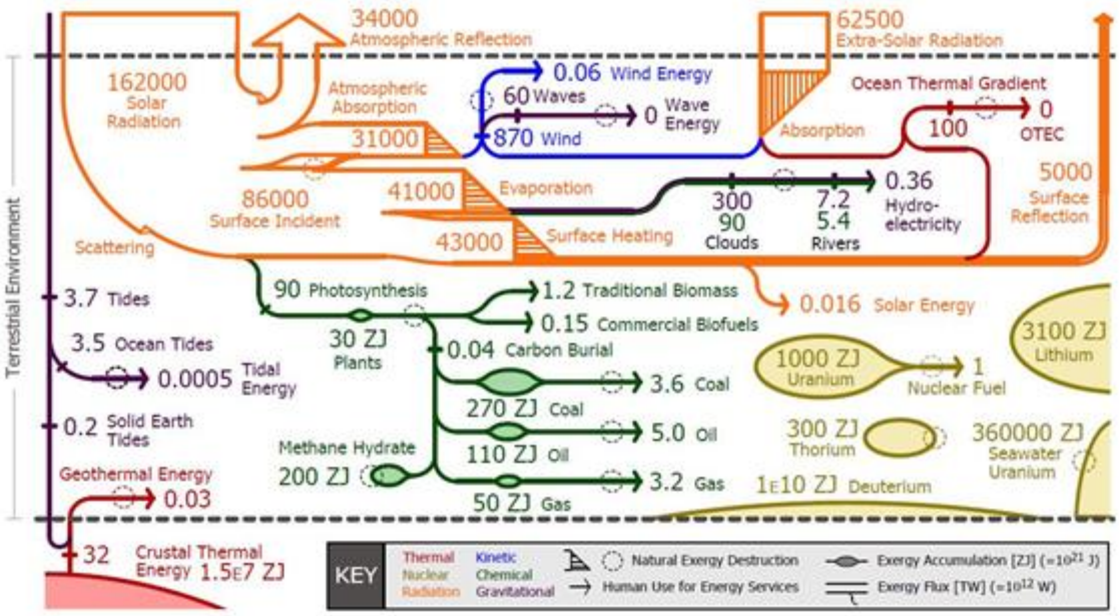

Figure 11 - Natural resource reservoirs, flows and transformations modelled in terms of exergy on a global scale (Hermann, 2006)

Along similar lines, Gong and Wall (2001a) also modelled the earth's resource flows in terms of exergy, noting that the major exergy supply to the earth is from the sun. On yet a larger scale, Chen (2005) used the exergy concept to model the radiation received by the earth from the sun. An exergy budget of the terrestrial earth's consumption was also presented, illustrating the flow of exergy through the biosphere. More recently, Valero et al. (2010) used exergy to conduct resource accounting of the exergy capital of the earth. In addition to quantifying the earth's renewable and non-renewable resources, Valero also considered non-fuel minerals. By using exergy as the basis, it was possible to compare energy resource with non-fuel mineral resources. The results of the study show that the depletion of non-fuel minerals should be of much greater concern than energy resources. The study predicts that while non-renewable energy resource should last humanity for at least 574 years, non-fuel minerals would be depleted in only 191 years.

Exergy modelling of natural reserves is a useful concept, and may be considered an improvement upon 1st law approaches in this regard, but it is still subject to all the limitations described in 2.5. While the accuracy, depth and method of the above mentioned studies could be debated, it is clear that exergy is a powerful concept that facilitates holistic analyses of complex large scale systems.

2.6.2. Sustainability assessment of societies

As the ability of the exergy concept to model resource consumption and depletion is evident from the previous section, studies have been conducted that assess the sustainability of societies ranging from a city to national scale.

The first sustainability analysis of a society using exergy was performed by Wall (1987) for Sweden. The resource base of the society was categorised into eight suitable sectors and its resource consumption was quantified in terms of exergy. In 1980, the Swedish society used 2539PJ with a net output of 500PJ. Following Sweden, Wall (1990) analysed the Japanese society using the same methodology. The study showed that in 1985, the net exergy input to Japan was 18EJ with a net output of 3.8EJ. Similarly, the Italian society was analysed by Wall et al. (1994) using the same method, illustrating that the total exergy input was 8300PJ with a net output of 1500PJ (Figure 12).

Chen et al. (2006) conducted the resource accounting of the Chinese society in the year 2000 using exergy as a basis. Various sectors of the Chinese economy were analysed, such as industries, transportation, household and the commerce sector. The total exergy input to the Chinese economy was 64.76 EJ, while the total exergy output was 12.8EJ resulting in an exergy efficiency of 20%. Similarly, Hammond (2001) used the exergy method to analyse the performance of the UK energy system. The article divided the UK energy system into four sectors and used the average exergy efficiency of each to assess their performance. One conclusion from the study was the CHP could play a significant role in recovering waste heat in the electricity generation sector.

Nielsen and Jørgensen (2015) presented a detailed structure of the Danish island of Samso and conducted its sustainability analysis. Some basic exergy based indictors were used to assess each sector separately as well as the society as a whole. The overall exergy efficiency was 114%, suggesting that the island produced more exergy than was supplied to it. The high efficiency was due the establishment of 21 windmills that made the island a net electricity producer. Additional measures such as straw consuming district heating plants also improved its exergy efficiency. It is noteworthy to mention here that the study did not consider its connection with the mainland, and therefore neglects this exergy capital expenditure on the island from the mainland.

A sustainability analysis of Norway was conducted by Ertesvåg (2005) using exergy as a basis. The method used was extended exergy analysis (EEA) which also takes into account the resource consumption due to labour and capital. Exergy values are assigned to labour and capital fluxes in order to conduct a more complete analysis, however, it cannot be considered a strictly thermodynamic analysis.

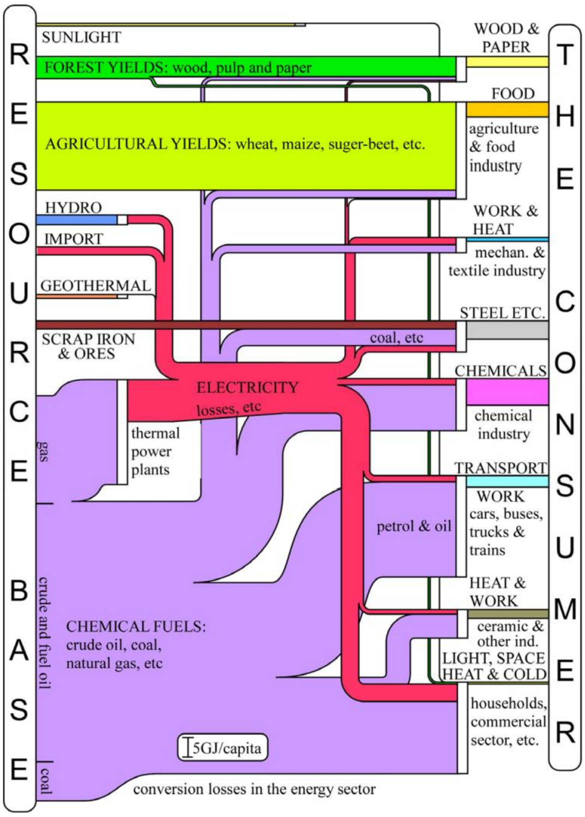

Figure 12 - Resource accounting of the Italian society in terms of exergy (Wall et al., 1994)

Emphasis has been placed on applying exergy to sustainability science by prominent researchers such as (Gong and Wall, 2001a; Gutowski et al., 2009; Lior, 2008; Rosen et al., 2008; Stougie and Kooi, 2011), which includes a study on the investigation of the relationship between exergy and sustainability by Stougie and Kooi, 2011). Consequently, exergy based environmental impact indicators have been developed (Díaz-Méndez et al., 2011; Tharumarajah and Koltun, 2007) A critical review of such environmental impact indicators was done by Ao et al. (2008) that highlight some of the shortcomings of the exergy approach to environmental impact assessment.

It is clear that exergy can be used, albeit with different methods, to conduct resource accounting of complex physical systems. Since exergy acts as a unified indicator, it becomes possible to make an intersociety comparison. Such a comparison of the sustainability of different countries using the exergy approach has been presented in the article by Ertesvåg (2001). Table 1 presents the comparison of four countries based on exergy efficiency. Additionally, each country is disaggregated into 10 sectors that represent the major resource flows through the economy. It can be seen from the table that the overall efficiencies for developed societies lie in the range of 20% - 30%. It is also noteworthy that industry sectors perform relatively better, while space heating has the lowest efficiency ranging from 2% - 6%. It should be noted here, the even at a societal level, the exergy efficiency of the built environment is low and therefore has room for improvement. Table 1 is a good example of how the exergy concept can be used to compare the sustainability of large and complex systems.

Table 1 - Exergy efficiency comparison of countries by sector , adapted from Ertesvåg (2001)

Exergy efficiencies for end-use sectors				
	Norway 1995	Sweden 1994	Italy 1990	Japan 1985
Forest industry	0.51	0.34	0.42	0.62
Food	0.17	0.12	0.16	0.34
Steel, metal	0.37	0.34	0.48	0.29
Chemical industry	0.6	0.4	0.43	0.49
Transportation	0.16	0.13	0.1	0.1
Lighting, etc.	0.17	0.24		
Mechanical work	0.5	0.5		
Space heating	0.06	0.07	0.02	0.03
Other industry	0.25		0.2	0.45
Households Service, Commerce	0.12 0.10	0.13	0.02	0.03
Total of end use	0.27	0.22	0.21	0.26

2.6.3. Buildings exergy management

Buildings have been analysed for their energy efficiency widely due to their high energy demand. However, energy analysis fails to account for the quality of energy which is a significant limitation when estimating the resource consumption in buildings. Consequently exergy analysis, which takes into account energy quality, can be useful for resource accounting in the built environment.

For this reason, buildings have been amply analysed using the so called "LowEx" approach (Hepbasli, 2012; Schmidt and Ala-Juusela, 2004; Shukuya and Hammache, 2002) This methodology aims to match the quality of energy supply and demand, thus minimising thermodynamic losses in the building. Figure 13 compares the conventional approach with the LowEx method, where energy quality matching is achieved. This effectively reduces entropy generation in the various energy transformations thus increasing exergy efficiency.

Figure 14 is a useful presentation of the variation of energy quality in supply and demand for buildings. It can be understood from the figure that fulfilling a low quality demand such as space heating through a high quality demand such as electricity is bad energy quality matching. A detailed guide on exergy management in the built environment and a guide for the LowEx approach can be found in Schmidt (2011).

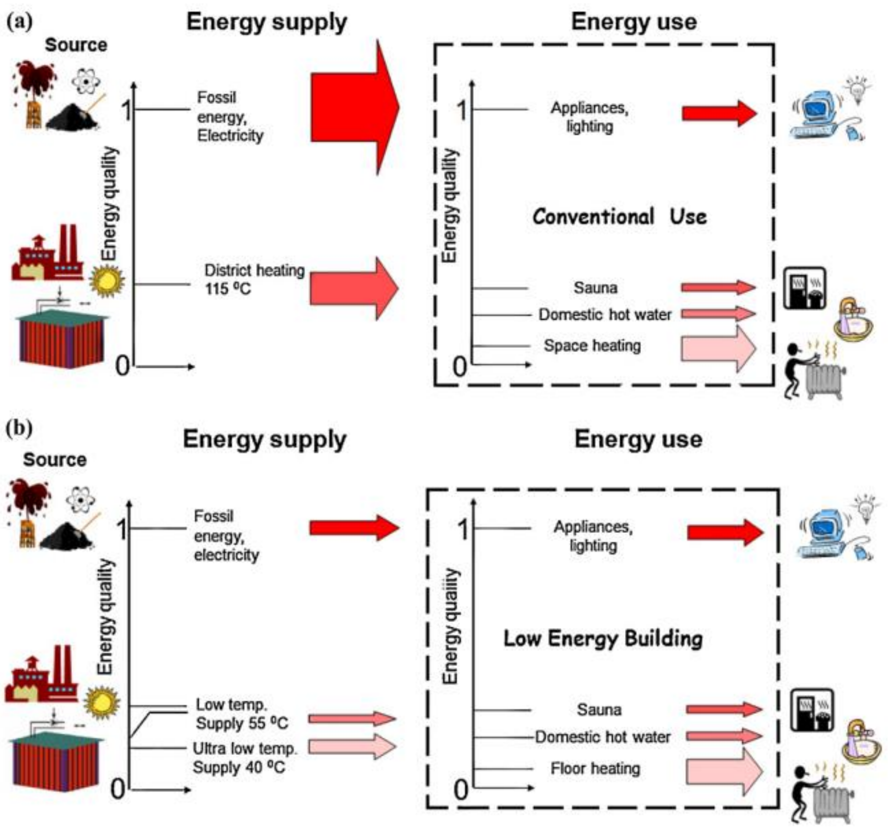

Figure 13 - Energy quality schematic (a) conventional use (b) Low energy building with supply and demand quality matching. Source (Hepbasli, 2012)

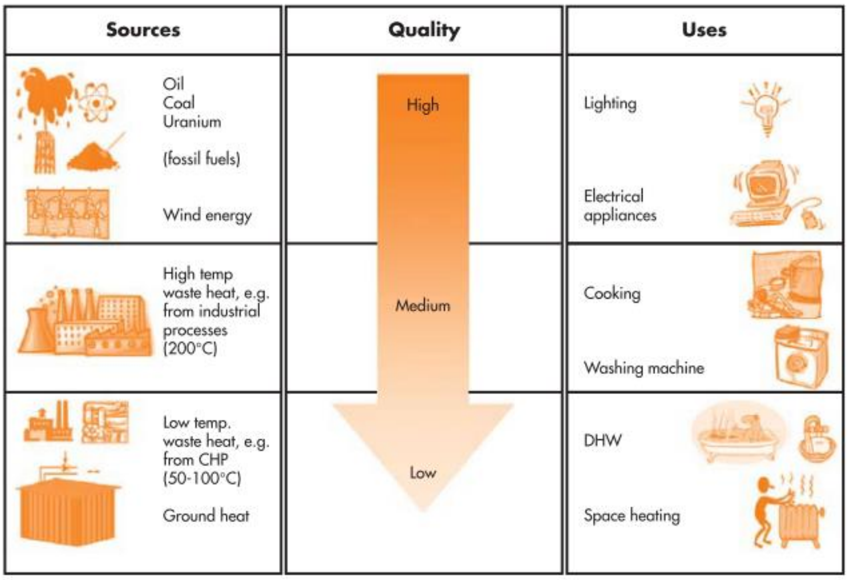

Figure 14 - Examples of variation in energy quality in supply and demand for buildings (Schmidt, 2011)

The general approach for calculating the exergy efficiency of a building is now briefly given. The detailed background for designing low exergy buildings can be found in Schmidt (2004). Using the LowEx approach, the building efficiency can be analysed based on dividing the flow of energy from the primary source up to the building envelope into seven stages or modules. The schematic in Figure 15 shows the modules for the energy flow of the building services energy utilization scheme.

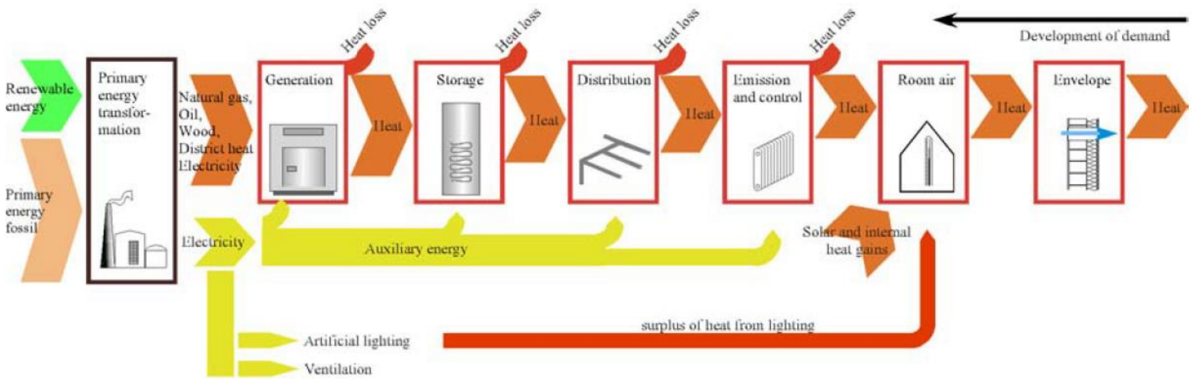

Figure 15 - Energy utilization in building services equipment (Schmidt and Ala-Juusela, 2004)

Based on this concept, many authors have argued that exergy management of buildings offers equal if not greater potential than energy analysis for natural resource savings in buildings (Garcia Kerdan et al., 2014). Some examples of application of exergy management in buildings are provided as follows.

Schmidt (2004) demonstrated the application of the LowEx approach with a case study of an office building in order to identify the locations of inefficiencies. Yucer and Hepbasli (2011) analysed a conventional boiler at a heating centre and a fan coil unit in a room, the exergy efficiencies were

13.4% and 37.6% respectively. Lohani and Schmidt (2010) compared the results of energy and exergy analysis by analysing ground/air source heat pumps and a conventional boiler in a typical residential building. The results of the study showed that ground source heat pumps were the most energy and exergy efficient technology as compared to the other two choices. Similarly Lohani and Schmidt (2010) analysed two air conditioning systems using the cumulative exergy consumption approach. Exergy management of buildings was automated by developing tools that integrate conventional energy analysis software with exergy analysis by Jahangiri et al. (2014). The need for dynamic simulation in exergy analysis of buildings arises from the fact that exergy results can be very sensitive to the reference environment temperature. Therefore, dynamic simulation tools have been developed by integrating software like modellica, MATLAB and energy plus etc.

Hepbasli (2008) also conducted a useful review on the exergetic assessment of renewable technologies for buildings and found that the exergy efficiency of for buildings ranged between 0.40% to 25.3%. Hepbasli (2012) followed this up by conducted a review Low Ex technologies for exergy management in buildings. Torio et al. (2009) conducted a similar critical review of articles on renewable energy based climatisation systems for buildings. The review article presented some useful conclusions along with listing the limitations of the approach. These reviews along with the case studies mentioned suggest that building’s exergy management is a mature concept and has clear benefits for assessing sustainability in the built environment.

2.7. Other areas of application:

While exergy analysis has been mainly used to investigate energy intensive systems, Bakshi et al. (2011) argues that it can be applied to any ‘well-defined’ system in any state. Consequently, it has been applied to a range of different areas, a brief overview of which is now provided.

It is a concept that has been adapted in several disciplines for the analysis of systems. It has been merged with ecosystem analysis, evolution theory, social theory, economics, policy and decision making to form possible solutions to multidisciplinary problems. Its use in economics and environmental science has given birth to exergoeconomic (Kanoglu et al., 2007; M. A. Rosen, 2002; Tsatsaronis, 2007) and exergo-environmental analysis (Kanoglu et al., 2007; Meyer et al., 2009). It has also been incorporated into the life cycle methodology the form the exergy life cycle assessment method (ExLCA) (Granovskii et al., 2008b; Grubb and Bakshi, 2011; Koltun and Tharumarajah, 2008). Valero used exergy as a basis for condition based preventative maintenance in energy systems. A series of articles were published that developed that area of exergy based diagnostics for energy systems (Correas, 2004; Lazzaretto et al., 2006; Valero, 2004; Valero et al., 2002; Verda et al., 2003).

In the area of biological systems, exergy has been used as an indicator for biological processes performance, with some pioneering works by Susani et al. (2006). For example, photosynthesis in plants has been investigated by Petela (2008) using exergy analysis. Valero et al. (2009a) coined the terminology, physical hydronomics (PH), which uses exergy to create profiles of rivers and water bodies in order to map their resource value. This concept is further explained in chapter 7 in which it is used for modelling water flows in a food factory.

Even though the versatility of the exergy concept allows it to be applied to different types of systems, it cannot be used unrestrainedly (Ao et al., 2008). Keeping in view the limitations of the exergy concept, it should be used with care so as to produce reliable results. Perhaps, the main use of exergy analysis lies in its application to engineering systems for the purpose of identifying thermodynamic losses (Granovskii et al., 2008b). The next section provides an overview of exergy analysis in the industry.

2.8. Application of exergy to manufacturing

The last few decades have seen numerous applications of exergy analysis to industrial systems. A review article by Dewulf et al. (2008) categorized the research in this area into (i) methodological developments and (ii) applications to specific processes. An example methodology is the cumulative exergy analysis (CExC), which extends the boundaries by considering the exergy consumption in the full chain of production processes rather than a specific one. Extended exergy analysis (EEA), developed by Sciubba (2001) adds to the CExC concept by accounting for capital, labour and the costs associated with treatment of environmental waste. The specific extended exergy was defined as the sum of thermodynamic exergy, and the equivalent exergy of capital, labour and environmental remediation activities.

Any physical system can be described by its thermodynamic properties, at a state in time. Manufacturing systems are no different, consequently Gutowski et al. (2009) presented a general thermodynamics based methodology for resource accounting in manufacturing. Since the approach offers a systematic and scientifically established method by which manufacturing processes can be examined, a simplified description of it is provided now.

The manufacturing process is modelled as an open system (Control volume) having mass, heat and work interactions. Figure 16 shows the input and output streams for a general manufacturing process that converts raw material to a finished product using the energy supplied. As a result of the production process, some waste material or energy (in the form of heat) is also lost. Each flow is characterized by its enthalpy, entropy and exergy. Additionally, since all real processes are irreversible; exergy is also consumed within the open system which is associated with entropy generation. This exergy consumption due to entropy generation is called exergy destruction and is depicted inside the control volume in Figure 16.

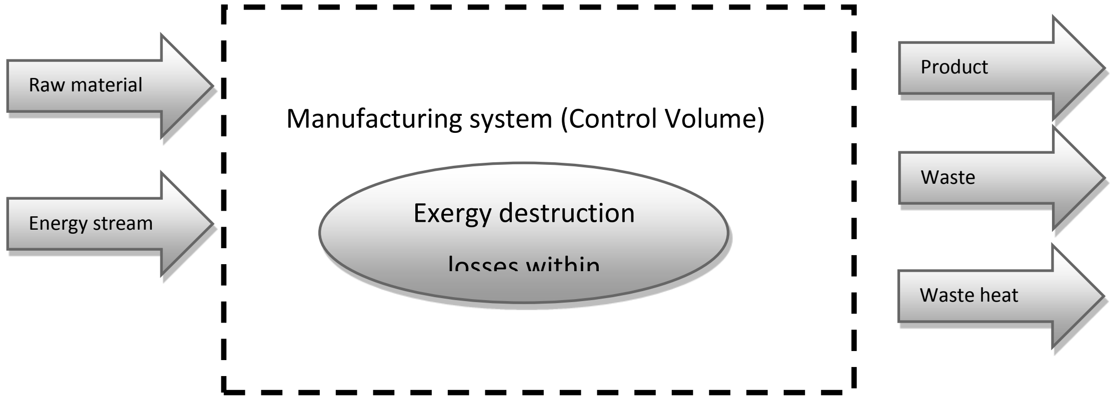

Figure 16 - Simplified version of approach to thermodynamic analysis of resource in manufacturing (Gutowski et al. (2009))

Considering the process operated between times t_1 , t_2 and the mass that enters and are denoted by m_i and m_e respectively, the general mass, energy and exergy balances can be written as follows.

The mass balance:

$$\text{Mass Input - Mass Output = Mass accumulation}$$

$$\sum_i m_i - \sum_e m_e = m_2 - m_1$$

Where all quantities with subscripts *"i"* and *"e"* are input and exit flows, and those with subscripts *"2"* and *"1"* are at time 2 & 1 respectively.

The energy balance:

$$\text{Energy input - Energy output = Energy accumulation}$$

$$\sum_i (e - Pv)_i m_i - \sum_e (e - Pv)_e m_e + \sum_i (Q_i)_{1,2} + (W)_{1,2} - \sum_o (Q_o)_{1,2} = E_2 - E_1$$

Additionally, *"e"* and *"v"* are the specific enthalpy and specific volume respectively. The absolute pressure and temperature is denoted by *P* and *T;* and the heat supplied or emitted into the environment is *Q*.

The exergy balance:

$$\text{Exergy input} - \text{Exergy output} - \text{Exergy consumption} = \text{Exergy accumulation}$$

$$\sum_i ex_i m_i - \sum_e ex_e m_e + \sum_i Ex_{Qnet} + Ex_{Wnet} - Ex_{dest} = Ex_2 - Ex_1$$

Where, *Ex* and, *W* represent Exergy and the net-work input to the system. Finally, Ex_{Qnet}, Ex_{Wnet} and Ex_{dest} are the exergy associated with net heat input, net-work input and exergy destruction respectively.

Establishing the exergy balance for a system allows one to analyse it using exergy analysis. In a review article about the application of exergy analysis in the industry, Boroum and Jazi et al. (2013) classified its applications into (i) exergy analysis of the industrial sector in different countries, (ii) exergy analysis of different industries within one country and (iii) exergy analysis of specific devices. Boroum and Jazi et al. (2013) advocate the use of exergy analysis for industry and claim that it produces results that are more representative of reality in comparison with energy analysis. From the comparison of energy and exergy efficiencies in different industrial processes as shown in Table 2, it is evident that exergy efficiency is markedly lower than that of energy efficiency. The consistent significant difference between the two efficiencies highlights the importance of considering the 2$^{\text{nd}}$ law of thermodynamics in analysis of industrial processes. This difference in efficiency was attributed to the fact that energy efficiency does not consider energy quality.

Table 2 - comparison of energy and exergy efficiencies in selected industries (Boroum and Jazi et al., 2013)

Process	Energy efficiency (%)	Exergy efficiency (%)
Petroleum refining	~90	10
Residential heater (fuel)	60	9
Domestic water heater (fuel)	40	2–3
Coal gasification (high heat)	55	46
Steam-heated reboiler	~100	40
Blast furnace	76	46
High-pressure steam boiler	90	50

Furthermore, Boroum and Jazi et al. (2013) classified the sub-sectors in the industry as illustrated in Figure 17.

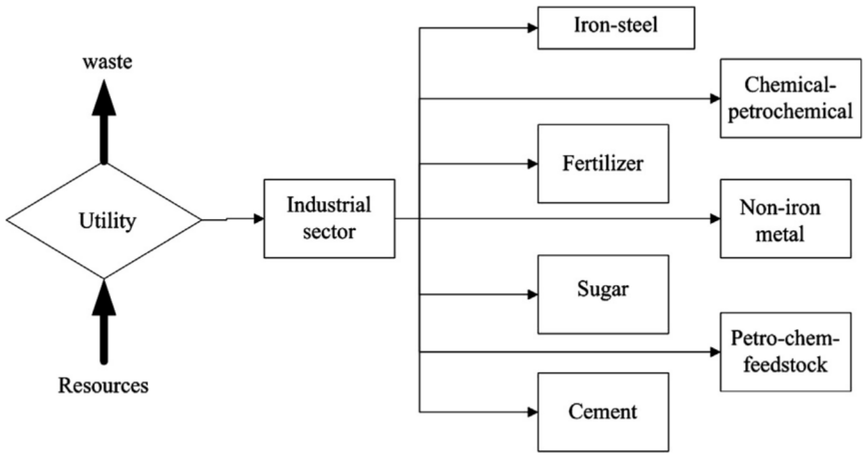

Figure 17 - Classification of the application of exergy analysis in the industry (Boroum and Jazi et al., 2013)

The cement, chemical-petrochemical and iron-steel industry have usually attracted much attention from exergy practitioners. For example, Sun et al. (2010) modelled the steel manufacturing process by combining exergy analysis with the methods of specific energy consumption analysis. Chen et al. (2009) undertook a study of an eco-industrial park and quantified the effect of process improvements in the park in terms of exergy. The exergy and exergoeconomic analysis of a complete cement plant in Gazientep, Turkey was conducted by Atmaca and Yumrutaş (2014). The overall exergy efficiency of the cement plant was found to be 38.99%, where significant improvement potential was identified in the pyro-processing tower, rotary kiln and grate clinker cooler components of the plant. Additional examples of exergy analysis in cement manufacturing can be found in the review article by Madlool et al. (2012). Rivero (2002) documented the applications of exergy analysis in petroleum refining and petrochemical industries. The exergy analysis of a glass manufacturing process was carried out by McKenna (2009) for which the overall exergy efficiency was 22%. A pulp and paper mill in Izmit, Turkey was analysed by Utlu and Kincay (2013), revealing that the production facility's mechanical and physical steps performed at exergy efficiency ranging between 30.2% - 94.2%. Similarly, Gong (2005) applied the exergy method to a pulp and paper mill in Sweden, and found the largest losses to appeared in the boilers. The exergy efficiencies of the sub-processes of the mill were found to range from 29%-96%. The cumulative exergy consumption (CExC) of a conventional textile washing process was analysed by Mozes et al. (1998). Based on experimental results, the electrical water heating process was found as the main source of exergy consumption. Furthermore, it was shown that replacing the electrical heating system with a district heating system could reduce the CExC by 57%.

Using exergy analysis, Branham et al. (2008) compared two metal casting technologies, a cupola furnace and an electric induction melting furnace. The exergy efficiency of the electric induction furnace was 79% as compared to 72% for the copula furnace. Further to this, Branham and Gutowski

(2010) also analysed a semiconductor manufacturing facility, and found it to be considerably energy intensive based on the specific electricity requirements of the process. The exergy efficiencies of the different sub-processes in semiconductor manufacturing plant were orders of magnitudes lower than processes in other industries and ranged between 10^{-2} and 10^{-4}. Branham and Gutowski (2010) attribute this low value of exergy to the fact that “macro” amounts of energy and materials inputs are required to effect micro and Nano scale processes.

The examples of industrial process exergy analysis mentioned thus far, and the conclusions of their respective authors suggest that exergy analysis is an appropriate tool for industrial systems efficiency assessment. However, with all the case studies mentioned, the focus is only on the process while neglecting the building that houses the facility. This is in line with tradition, as historically, manufacturing processes are studied separately to the building processes. However, a recent trend of considering the factory as a whole system has emerged that might improve upon the current methodologies for resource accounting in factories. To this effect, section 2.9 continues this discussion in detail in order to specify the knowledge gap that is to be filled in this research.

2.9. Integrated approach to factory analysis

Traditionally the processes in a factory are studied separately to the building that houses it. Additionally, the analyses are mostly limited to the use of the 1st law of thermodynamics, for example Henningsson et al. (2004) presented the financial savings achieved through improving resource efficiency in the food industry within in UK. In their analysis, mass and energy flows through the system were analysed in order to link them with the financial savings achieved. Duflou et al. (2012) reviewed the methods used for increasing the resource efficiency in discrete part manufacturing. Their review makes it clear that within the domain of resource efficient manufacturing, analysis is predominantly based on the 1st law of thermodynamics. Additionally, Duflou et al. (2012) suggest that in order for an analysis to be complete, a holistic understanding of manufacturing is required. This would allow the identification of greater resource reuse opportunities, thus having a greater impact on waste reduction and resource efficiency. A similar opinion has been expressed by other researches in the field, such as Evans et al. (2009) who suggest that a whole systems thinking approach is well suited to the current challenges faced by the movement towards industrial sustainability. Ball et al. (2013) highlight a similar concern, which is that the sustainability of manufacturing processes and that of the factory building in which they are situated are commonly studied separately. Resource optimization tools in manufacturing generally focus on discrete material flows, whereas for buildings the focus is on continuous energy flows.

Since factories comprise both the building and manufacturing processes, optimization methodologies and tools that combine the two might offer great potential for resource savings (Oates et al., 2011).

Conventional energy data analysis techniques that aim to consider both the processes and the building, albeit without considering the interaction between them, make use of energy and production data, combined with statistical techniques to make informed judgements about process improvements. Table 1 below lists some of these techniques and indicates whether they are applicable to building analysis, the industry or both.

Table 3 - Energy data analysis techniques Adapted from (ETSU, 1998)

Analysis technique	Buildings	Industrial sites	Description
Normalized Performance Indicators(NPI)	YES	NO	Benchmarking of buildings of similar type.
Specific Energy Ratio(SER)	NO	YES	Simple industrial process benchmarking.
Current and Past Comparison	YES	YES	Comparison against previous energy performance.
Trend line	YES	YES	Graphical display of energy use against time.
Profiles	YES	YES	To show consumption patterns over specific time periods.
Contour Mapping	YES	YES	3-D way of displaying energy profiles.
Lines of best fit	YES	YES	For approximating simple mathematical relationships between energy consumption and key drivers
Variances	YES	YES	To show deviation from anticipated energy performance
CUSUM	YES	YES	Cumulative sum of variances form standard performance – useful to identify changes in pattern of energy use.
Control Charts	YES	YES	Using predetermined controlled limits to alert exceptions to planned performance.

The main advantage of the techniques in Table 3 is the relative ease and speed of use and the fact that the data required is readily available. For example, unlike full simulations models, degree-day calculations can be carried out manually or within computer spread sheets. They have a transparency and repeatability that full simulations may not provide, however, these advantages don't make them a substitute for full energy simulations (Day and others, 2006). Manufacturing facilities are complex systems and their resource consumption is determined by a large number of factors. As such, a methodology that facilitates simulation and views the factory as a whole systems, could improve upon the state of the art in resource accounting techniques for factories.

Addressing this gap, Despeisse et al. (2012a) presented a conceptual model that used a whole systems perspective for factory analysis followed by its application to a case study Despeisse et al. (2012b). Herrmann and Thiede (2009) also presented an integrated model of a factory that comprised the production processes, the technical building services and the building shell which houses the other components. This is followed by its incorporation into a sustainability assessment tool and its application to a case study (Chen et al., 2014). In a review article by Herrmann et al. (2014), an overview of the approaches to measuring sustainability in factories is provided. According to the article, the requirement of a thorough understanding of a manufacturing system with the interlinked constituent components seems to be widely acknowledged by researchers. Herrmann further adds that for the analysis at the factory level, there is a common consensus that the factory comprises of three main partial systems; (i) the building services, (ii) the building shell and (iii) the production system. Based on previous work in this area, Herrmann presented a model of the factory of the future as illustrated in Figure 18.

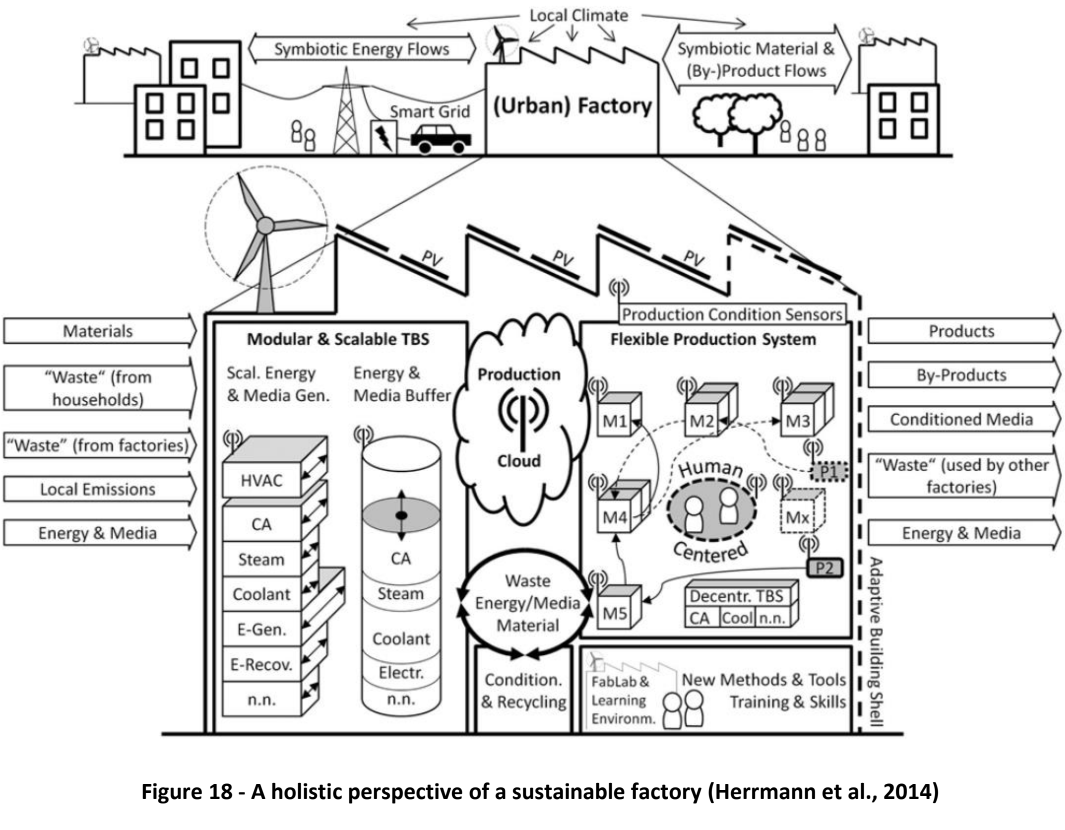

Figure 18 - A holistic perspective of a sustainable factory (Herrmann et al., 2014)

More recently Schlei-Peters et al. (2015) presented a methodology for factory analysis that also viewed it as an integrated system. The article brings to attention the fact that even though water and energy flows in a factory have interdependent effects, common analysis methods treat them separately. Schlei-Peters et al. (2015) tried to address this gap through their presented methodology and illustrated its application through a case study. Silvaa et al. (2015) presented an analysis of scientific publications in the area of green manufacturing, to identify the main research areas and future trends. The results of the analysis showed that among the topics that received attention from researchers, methodologies for monitoring and evaluation of energy consumption in manufacturing was one of the issue that stood out.

From the literature discussed so far, it can be understood that energy and mass analyses are commonly used for assessing the sustainability of factories, with a recent trend towards a more holistic perspective. Frequently, resource consumption is quantified using thermodynamic quantities based on the 1st law (mass and energy) which are always conserved. Quantifying the consumption of resources based on quantities which we know are always conserved can seem counter-intuitive and may therefore lead to misleading results. As resources flow through systems, their mass and energy remain conserved, yet their usefulness is lost after the mass and energy transformations occur. In other words, mass and energy flows degrade in quality as they undergo their respective transformations. Techniques based on the 1st law do not take into account the quality of resource flows and therefore allow only a partial analysis. It is therefore hypothesized that a methodology that views the factory as a whole system, and is based on the 2nd law of thermodynamics, might improve upon the state of the art in resource accounting methods for manufacturing systems. From the identification of this knowledge gap, the refined research question is formed.

2.10. Refined research question

Following on from the previous discussion, and keeping in view the useful nature of the exergy for the purpose of natural resource accounting, along with a current trend towards a holistic analysis of factories, the following refined research question was developed.

Compared to an energy based approach, can an exergy based approach that is based on a holistic view of manufacturing systems be more effective at quantifying resource consumption?

The remainder of the thesis is devoted to presenting the developed novel methodology and its validation. Chapter 3 describes the research methodology used, while Chapter 4 presents the conceptual model itself. This is followed by three chapters that are case studies for its quantitative validation, while chapter 8 is devoted to its qualitative validation.

Chapter 3 Methodology

3.1. Chapter overview

This chapter explains how the research was carried out, what methods were used and provides the reasons behind their selection. The first section gives a brief introduction to the general research process, followed by some related background information. In the second section, the research design of the current project is described, a justification of the methods used along with their limitations is provided. Finally, a summary of the process is presented in the form of a table to guide the reader through the thesis.

3.2. The general research process:

Research is a logical and systematic search for new and useful information on a particular topic (Rajasekar et al., 2006). It is a systematic method of finding solutions to problems through an objective analysis. The prime objective of research work is to add to the existing knowledge base in the specific subject area. This understanding of formal research seems to be accepted by the wider community of scholars, for example, Robson (2016) shares a similar view, that research conducted should be systematic, objective and should conform to the laws of ethics. He further adds, it is a methodical investigation that should lead to an increase of knowledge in the subject area. Rajasekar et al. (2006) list the main objectives of the research as follows,

i. To discover new facts and verify, test existing important facts
ii. To analyse a phenomenon to identify the cause and effect relationship
iii. To develop new scientific tools, concepts and theories to solve and understand problems
iv. To overcome scientific, non-scientific, social or daily life problems

As it will be described in the subsequent sections of this chapter, a major aim in the current research project pertains to objective number three in the above list, the development and validation of a new scientific concept to solve a problem in the subject area of industrial sustainability.

3.2.1. Types of research:

Saunders et al. (2011) classified research into two broad types, fundamental or basic research and applied research. **Basic research** deals with the investigation of the fundamental principles of a particular phenomenon, and may not have immediate applications in the real world. On the other hand, **applied research** is conducted upon real world problems, the outcomes of which could be immediately applicable. In applied research, problems are solved using principles and theories that are well known and accepted by experts in the field. The current research project is of the later type, as it deals with the real world problem of devising an effective method for measuring industrial sustainability.

3.2.2. Research method and methodology:

Before the overall research design is presented, for the benefit of the reader, it is important to clarify the distinction between method and methodology**. Research methodology** is the overarching framework in which research is conducted; it constitutes the systematic procedure that allows a researcher to add to the body of knowledge in the selected subject area. It is important to distinguish it from **research methods** which are the various procedures and algorithms used to find specific solutions to problems in the research. They include methods such as mathematical modelling, statistical approaches, numerical schemes etc. The description of this project's overall research design which describes the research methodology is the subject of the following section.

3.3. Overall research design:

This section describes the overall research design used in the course of this PhD project, the reasons when necessary, for the selection of methods used are provided. At the end, its summary that reflects the thesis structure is presented in the form of a table.

Figure 19 depicts the process of research in the form of a flow diagram; each step in relation to the current research will now be described.

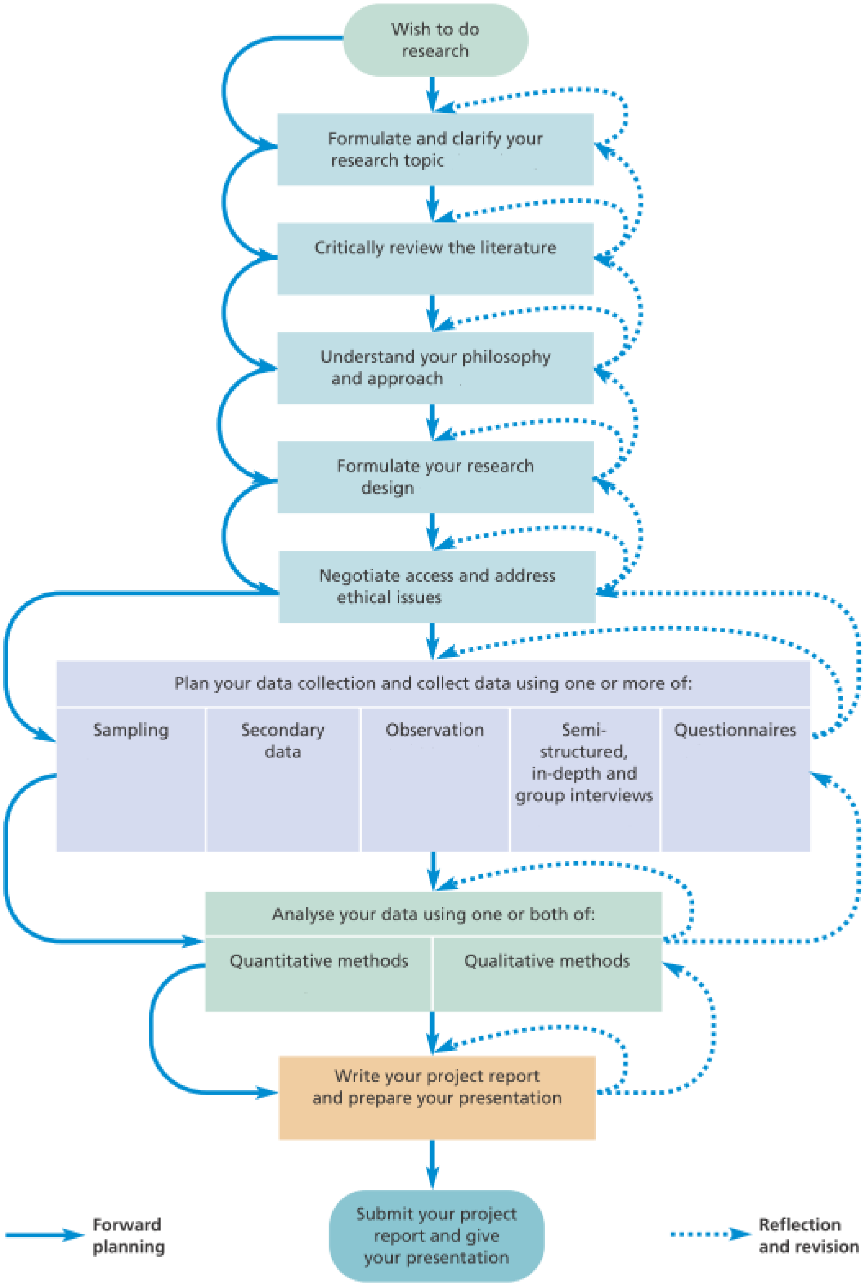

Figure 19 - The research process illustrated (Saunders et al., 2011)

3.3.3. <u>Formulation and clarification of research topic:</u>

This is the initial phase in which the research aim if clarified, has been described through sections 1.2 to 1.4. This PhD project was funded through the KAP (KAP) project, therefore the general area of research was aligned with the broader goal of KAP (KAP), i.e. sustainable manufacturing. After an initial review of relevant literature, the general research aim was formed and is repeated below, *The aim of this research is to develop a methodology that improves upon the state of the art in methods for measuring industrial sustainability.*

The objectives that would allow achieving the above aim are listed in section 1.6, but are not repeated here.

3.3.4. Literature review:

The literature review is an important part of the process and forms the knowledge base from which research can be carried out. A review of relevant literature was described in detail previously (Chapter 2) in which the methods used for measuring industrial sustainability were described. Resource efficiency was identified as a proxy to measuring industrial sustainability, consequently the focus of the PhD was further narrowed from sustainability to resource accounting methods in manufacturing. This helped clarify the objectives of the research, with the possibility of arriving at well – defined and quantifiable results. Among the broad methods used for measuring resource efficiency in manufacturing, exergy analysis was chosen as the method of choice. This choice is supported by the following reasons,

i. The exergy concept allows to model mass and energy flows in common physical units, thus allowing for a holistic analysis
ii. It accounts for the quantity as well as quality of resource flows

This usage of the exergy concept in conjunction with a recent trend of analysing a factory holistically allowed refining the research question, that consists of the following three main components,

i. How can the exergy method and the integrated approach to factory analysis be combined to create a holistic factory analysis concept?
ii. How effective is the devised approach at quantifying sustainability or resource consumption as compared to the energy based approach?
iii. If the approach is effective and practically applicable, is it valuable for the industry?

3.3.5. Formulation of research approach and design:

The clarification of the research topic, and the resulting refined research question presented a need to devise a concept for factory resource efficiency analysis that combined exergy analysis with the holistic view of the factory. The resulting novel approach to factory analysis is to be presented in the upcoming chapter.

After the novel approach/concept was developed, its validation pertaining to the research objectives needed to be carried out. First and foremost, it was mandatory to illustrate the practical application of the approach to real factory environments. A case study approach that would illustrate the application of the novel analysis method was well suited for this purpose. Each case study separately, and finally together as a group, would be used to answer the generated research question and address the research objectives. Therefore, an understanding of the research methods was required, which are described as follows.

Research methods have been broadly classified into quantitative and qualitative approaches (Saunders et al., 2011), a judicious selection of which forms an important part of the research process. Quantitative methods involve data collection and analysis techniques that use and generate numerical data while Qualitative methods result in non-numerical data. Saunders et al. (2011) organized the choices for research methods in a way that was particularly useful for this PhD project, see Figure 20.

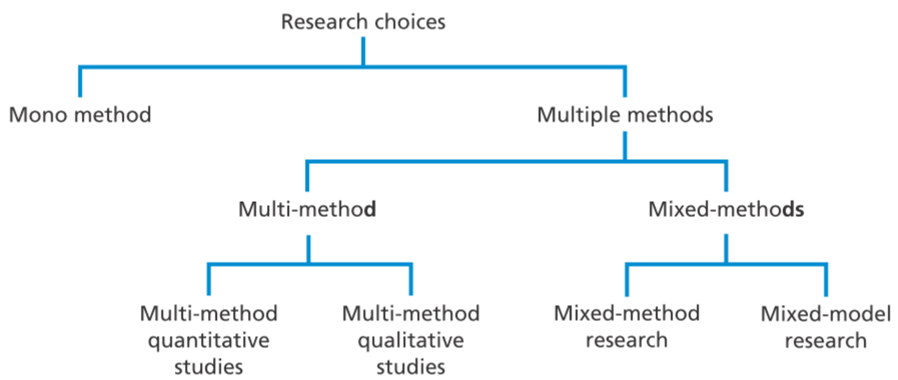

Figure 20 - Research method choices (Saunders et al., 2011)

In reference to Figure 20, the term 'mono method' refers to the choice were a single method is used for data collection and analysis, the alternate being 'multiple methods' where different methods are combined. Multi-method approaches refer to the usage of different methods, but constrained within one domain. For example, multi-method quantitative studies would use multiple methods, all of them being quantitative. Mixed-model research implies methods that combine quantitative and qualitative (in parallel) resulting in methods that cannot be classified as either. Finally, mixed method research combines quantitative and qualitative methods in series, therefore the resulting methodology is composed of clearly defined steps that belong to either the quantitative or qualitative domain.

Within the current project, mixed-method research was used, the reasons for which were evident and are discussed now. Since the project involved the use of an energy analysis technique, it naturally fell into the quantitative category. In an energy analysis, it is necessary to collect quantitative data and conduct the analysis using a scientific approach. The energy and exergy analysis of case studies were used for validation of the devised novel method. Due to the nature of the manufacturing design, and depending upon the availability of data, different quantitative analysis methods were used, thus resulting in a multi-method quantitative approach. To expand more on this, case study one used data collection directly from the factory site which was then used for analysis. The focus of the first case study was the building; therefore an exergy analysis designed for buildings was used. This had no elements of chemical analysis of the factory flows involved. Case study two is based on experimental data from a previously conducted energy analysis of a production facility. In addition to the approach adopted in the earlier case study, this one also involved the chemical exergy analysis of mass flows at a basic level. Finally case study three was heavily based on the chemical analysis of substances in a factory's effluent water. The three case studies combined therefore display different quantitative analyses techniques. This was necessary as the case studies were chosen of varied nature so the developed approach could be illustrated on differing manufacturing designs.

If the newly devised factory analysis method emerged as one that could have potential benefits for decisions makers in the factory management, then its impact and value to the industry had to be gauged. This was done through a 'multi-method qualitative analysis' that aimed to gain insights into practical application and potential benefits for the industry. It could also identify potential gaps in the proposed novel method for measuring resource efficiency at factories. The choice of 'multi-method qualitative analysis' was based on the fact that insufficient data was acquired through the preferred but time consuming process of interviewing. Therefore a webinar followed by a survey and written responses through a social media platform were also used. .

Although the research can be categorised as mixed methods research, the quantitative part dominates. As Saunders et al. (2011) pointed out, "often either quantitative or qualitative techniques predominate" and such is also the case in this PhD project. The quantitative sections form the bulk of the research work, as it was necessary to illustrate its use and potential benefits for decision makers in factory management. It is only after such an illustration was done, that insights into its practical worth for the industry could be assessed. Keeping in view the time and resource limitations imposed upon a PhD project, Chapter 8 describes the qualitative part of the study designed assess the practical worth of the approach for the industry.

3.3.6. Data collection:

The mixed methods research design required the use of different data collection techniques. For the quantitative part of the study, each case study was selected based on the following merits,

i. Its potential to address a specific objective for the PhD project
ii. Practical considerations, such as access to the case study

Data collection for a case study proceeded by either acquiring data first hand, or through personnel who had access to the facility. Therefore the data collection was a mixture of primary and secondary data. Table 4 below summarizes the information regarding quantitative data collection for this research.

Table 4 - Quantitative data collection summarized

	Type of data	Method/Equipment used	Remarks
Case study – 1	Primary & Secondary	- Data logging - Material sampling	Data for this case was acquired through factory visits, not by the author himself, but rather the research team which was involved with the project. Furthermore, data logging equipment was tested and sent to the facility to be installed by onsite technicians. Additional data about the manufacturing processes was provided by the factory management.
Case study – 2	Secondary	N/A	Data for this case study was purely secondary, as it was based on experimental work of another researcher and the study was conducted in collaboration with him.
Case study – 3	Primary	- Data logging - Material sampling - Laboratory tests	Data was collected by the author himself through visiting the factory, data logging equipment, and water sampling. Data related to water quality was acquired through the use of a public laboratory facility.

Following the quantitative analysis, a multi-method approach was used to acquire data from experts, industry practitioners and experienced researchers in sustainable manufacturing. Due to the nature of approach, and an uncommon usage of the exergy concept in the industry, a questionnaire approach would draw fewer responses. To this effect, face to face interviews, online interviews, webinar presentations, online questionnaires were all used to acquire the data set. More detail regarding this section of the research is to be presented in Chapter 8.

3.3.7. Data analysis:

The quantitative data analysis was based on exergy analysis, followed by a statistical analysis of the results. These methods proved successful at producing a comparison against the conventionally used 1st law of thermodynamics based approach.

The goal of the qualitative section was to evaluate the significance/value of the devised novel approach to measuring resource efficiency in factories. Additionally, the barriers and drivers of its use for the industry were to be identified. In view of these goals, the resource and time limitations upon the PhD project, thematic analysis appeared to be the most appropriate analysis method of choice. Themes are consistent patterns that emerge across data and are associated to specific research objectives. This analysis method was chosen because a significant amount of qualitative data was acquired through interviews and questionnaires. Organizing the collected data into clear themes allowed translating the descriptive data into measurable results that would indicate the value and significance of the approach for the industry.

3.3.8. Writing phase:

The final phase of research is presentation and writing/publication of the work. It should be noted that writing may not always come sequentially after the research has been completed, rather it can proceed in parallel and be actually a part of the research process itself. A similar approach was taken in this PhD project; the written outputs are listed in section 1.8. This thesis however, provides the full description of the work and the possible future research directions.

3.3.9. Limitations of the research design:

This section describes the limitations of the research design as recognised by the author. The validity and quality of research output is based on four generally accepted concepts: construct validity, internal validity, external validity and reliability (Yin, 2009). Of these, external validity represents a limitation of the current research. It is the degree to which the results can be generalised, which can be difficult when dealing with manufacturing systems. Due to marked variation in the manufacturing design for different products, there may be concerns in using a single case study as a basis for scientific generalisation. In order to tackle this issue, multiple case studies of varied manufacturing design were used. Each case study not only belongs to a different industry, but is composed of entirely different process as well. Additionally, each case is used to illustrate a portion of the novel approach presented; all three cases combined illustrate all facets of the developed method. While it is understood by the author that the three case studies do not cover all manufacturing process and designs; based on the variation among them, it is argued that the approach could be applicable to manufacturing in general.

3.4. Chapter summary:

Table 5 below summarizes the research design and shows how each chapter is associated with a part of the research process and addresses the objectives. While the below table may seem like a linear process, it is not the case with research in reality and a simplified representation of a vacillating process.

Table 5 - Summary of the research design in relation to the thesis structure

Phase of the research process	Objective addressed	Chapter
Specify and formulate objectives	- The formulation of the objectives themselves	Chapter 1 : Introduction and overview of the thesis
Literature review	- Review relevant literature to identify knowledge gap	Chapter 2 : Literature review
Understand approach and research design	- Design methodology for conducting the research	Chapter 3 : Methodology
Concept generation	- Develop novel methodology for measuring industrial sustainability	Chapter 4 : A novel method to factory resource accounting
Data collection/analysis – 1	- To illustrate its application to a real factory environment	Chapter 5 : Case study – Engine cylinder head production line
Data collection/analysis – 2	- To test robustness by applying to different manufacturing environments - To show the application of the concept at industrial symbiosis level	Chapter 6 : Case study – Jaggery production
Data collection/analysis – 3	- De illustrate application to different manufacturing environment (through modelling of water flows)	Chapter 7 : Case study – Food production

Data collection/analysis – 4	- Gauge significance/value to the industry	Chapter 8 : Significance to the industry
Reflection and future work	- Outline findings and novel contributions - Outline strengths and limitations of the novel approach to factory analysis - Identify future research directions	Chapter 9 : Discussion, conclusions and future work

Chapter 4
A novel approach to resource accounting in factories

4.1. Chapter overview:

This chapter builds upon the literature review by presenting a conceptual approach to factory analysis that is designed to fill the identified knowledge gap. The literature review in Chapter 2 culminated in the identification of two arguments, that if combined could produce a potentially useful resource accounting concept for factories:

i. Considering the factory as an integrated system of production processes and the building would identify additional opportunities for resource reuse.
ii. Exergy analysis is a suitable method for quantifying resource consumption in manufacturing systems.

In other words, a conceptual model that views that factory as a whole system in which all flows are modelled in terms of exergy could potentially result in an effective methodology for resource accounting in factories. Such a conceptual model has been formed and is presented in the section that follows. Parts of this chapter are quoted verbatim from Khattak et al (2015) but for reasons of clarity, this source will not be repeatedly cited.

4.2. The conceptual approach:

Previously, Despeisse et al. (2012a) presented an integrated approach to factory analysis which was based on the concept of industrial ecology (IE). Industrial ecology is defined as the study of interactions and interrelationships both within industrial systems and between industrial and natural systems. It is based on an analogy between the industrial and natural ecosystem where the natural ecosystem is considered the ideal model and the industrial ecosystem strives to achieve the ideal goal. See Figure 21 for the conceptual model created by Despeisse et al. (2012a), which is essentially an IE model at the factory level based on the 1st law of thermodynamics; where material, energy and waste (MEW) flows connect the components of the model. In this idealised model, the factories and other human development, including the manufacturing system elements reside in what is termed the technosphere. The ecosphere represents the natural environment that serves as a source and sink for resources and wastes respectively. Despeisse et al. (2012a) divided the factory into three main components; the manufacturing operations, its supporting facilities and the building. This subdivision into three modules was similar to the model previously proposed by Hesselbach et al. (2008), and can be considered a generally accepted view of the integrated model of the factory environment (Herrmann et al., 2014).

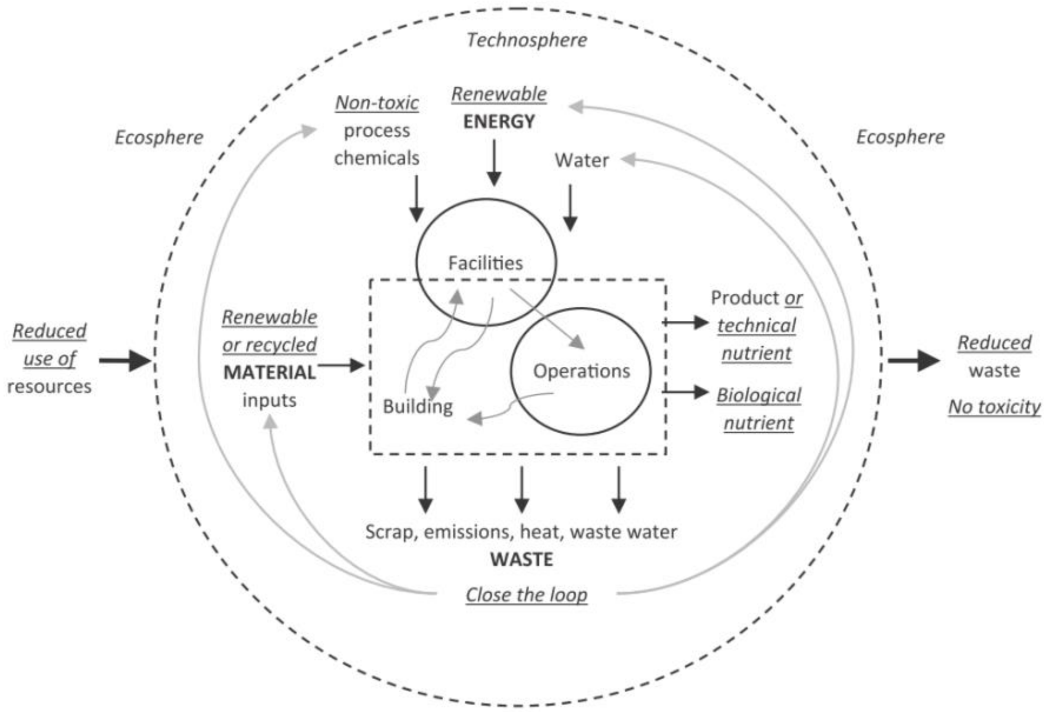

Figure 21 - Manufacturing ecosystem model with MEW flows Despeisse et al. (2012a)

An important facet of the model in Figure 21 was that it depicted an ecosystem; in which the emphasis was not on local optimizations but rather on the globally efficient use of resources. Furthermore, the manufacturing system model was resolved at the factory level so as to facilitate quick and effective decision making regarding efficient use of resources. A concept central to the model was of ‘closing the loop’ which basically refers to reusing resources in order to reduce waste. It is important to note here that a closed loop system cannot mean a truly sustainable system without the input of renewable energy supply. The natural ecosystem, which is the ideal sustainable system closes the loop but is supplied by renewable energy. Transforming industrial systems from linear to cyclical is only a part of the solution as it can only reduce the supply energy needed. Focusing on renewable supply on the other hand, constitutes the second part of the solution towards sustainable manufacturing. To this effect, Herrmann et al. (2014) presented a similar concept as depicted by Figure 18 in section 2.9 (not repeated here).

The purpose of this section is to present the novel concept, which essentially builds upon the previous works mentioned above by considering the mass, energy and waste flows as exergy flows. Figure 22 presents the concept which is similar to the one presented by Despeisse et al. (2012a) in its structure, but is different in terms of the flows that connect the systems together. All material, energy and waste (MEW) flows are modelled as exergy flows, therefore basing the model on the 2nd law of thermodynamics rather than the 1st law.

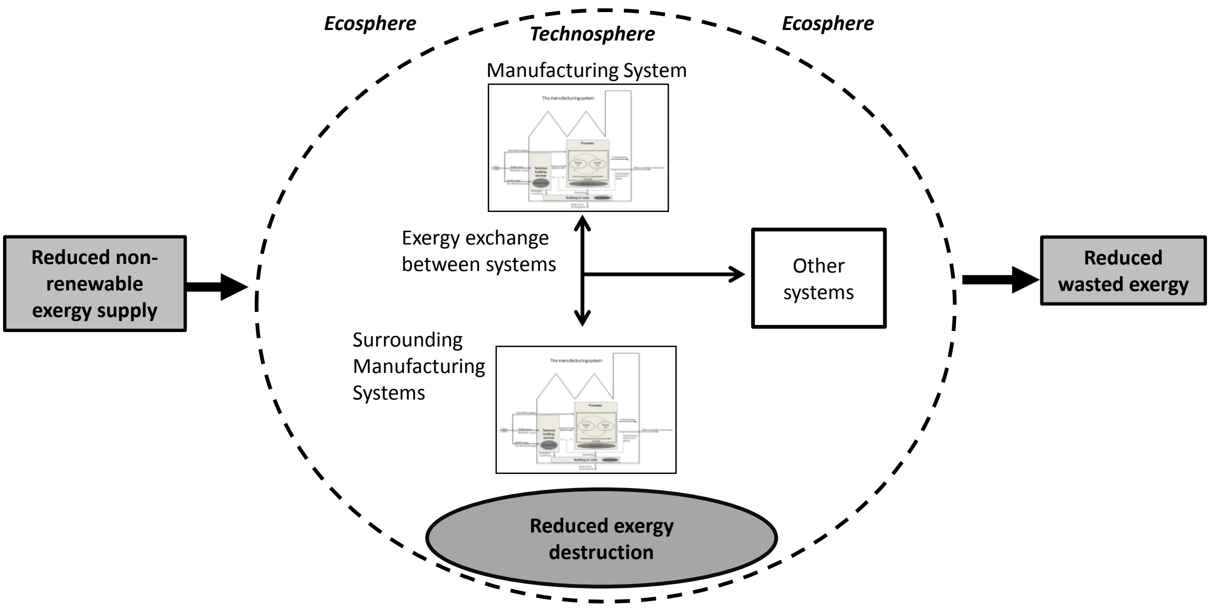

Figure 22 - A conceptual approach to facilitate sustainability in manufacturing systems

Additionally, the closed loop concept is further aided by the identification of exergy destruction. As mentioned earlier, closed loop systems that are supplied by non-renewables can never represent a 100% sustainable system, as resources are always consumed when they undergo the various transformations in the manufacturing environment. The use of the 2nd law of thermodynamics makes this aspect of resource consumption particularly clear. Therefore, the recycled resources can never form a self-sustaining loop unless exergy is supplied from renewable sources.

This consumption of natural resources is quantified as exergy destruction, which might be sourced by either renewables or non-renewables. It is argued that the depletion of natural resources that is relevant to the sustainability (or otherwise) of systems depends only upon the consumption of non-renewable reserves. Therefore, a 'closed loop' that represents a truly sustainable system would have zero destruction of exergy from non-renewable sources. Summarizing, improvements in resource efficiency may be directed towards two major goals,

i. To reduce the destruction of exergy from non-renewable sources
ii. To increase the proportion of renewable supply

Alternatively, natural resource consumption in a factory that leads to the depletion of natural resources can be indicated through,

i. The industrial system's demand for non-renewable exergy
ii. The exergy destruction within the sub-systems of the integrated industrial system

While non-renewable exergy demand indicates non-renewable resource consumption, the exergy destruction shows how efficiently the supply is used to produce the required product. This argument is supported by other researchers; for example Connelly and Koshland (2001) presented an industrial ecosystem evolution analogy for assessing the level of sustainability in industrial systems. They argued that the depletion of natural resources was associated with "consumption of non-renewed stock exergy". Similarly, Szargut et al. (2002) calculated the impact on the environment through an "ecological cost" indicator that made use of cumulative consumption of non-renewable exergy. Wall and Gong (2001b) detailed the different types of exergy that exist in nature and how it can be used to measure impacts on the natural ecosystem. The concept of sustainability was examined with relation to exergy and a strong recommendation was given for its use in all disciplines that lead to a sustainable future. In the article, Exergy based environmental indicators were developed and applied to case studies.

Figure 23 presents the conceptual model resolved at the factory level, which is the major novelty in the presented concept. It is suggested that this conceptual approach/model could serve as a decision making tool for improved resource efficiency in factories. Figure 23 illustrates the conceptual approach and shows a manufacturing system in which all material, energy and waste flows are represented as exergy flows. Considering both energy and mass flows on a common unit basis should facilitate the identification and quantification of possible reuse opportunities. The manufacturing system depicts the factory environment comprised of three sub-systems; the technical building services (TBS), the manufacturing processes and the factory building.

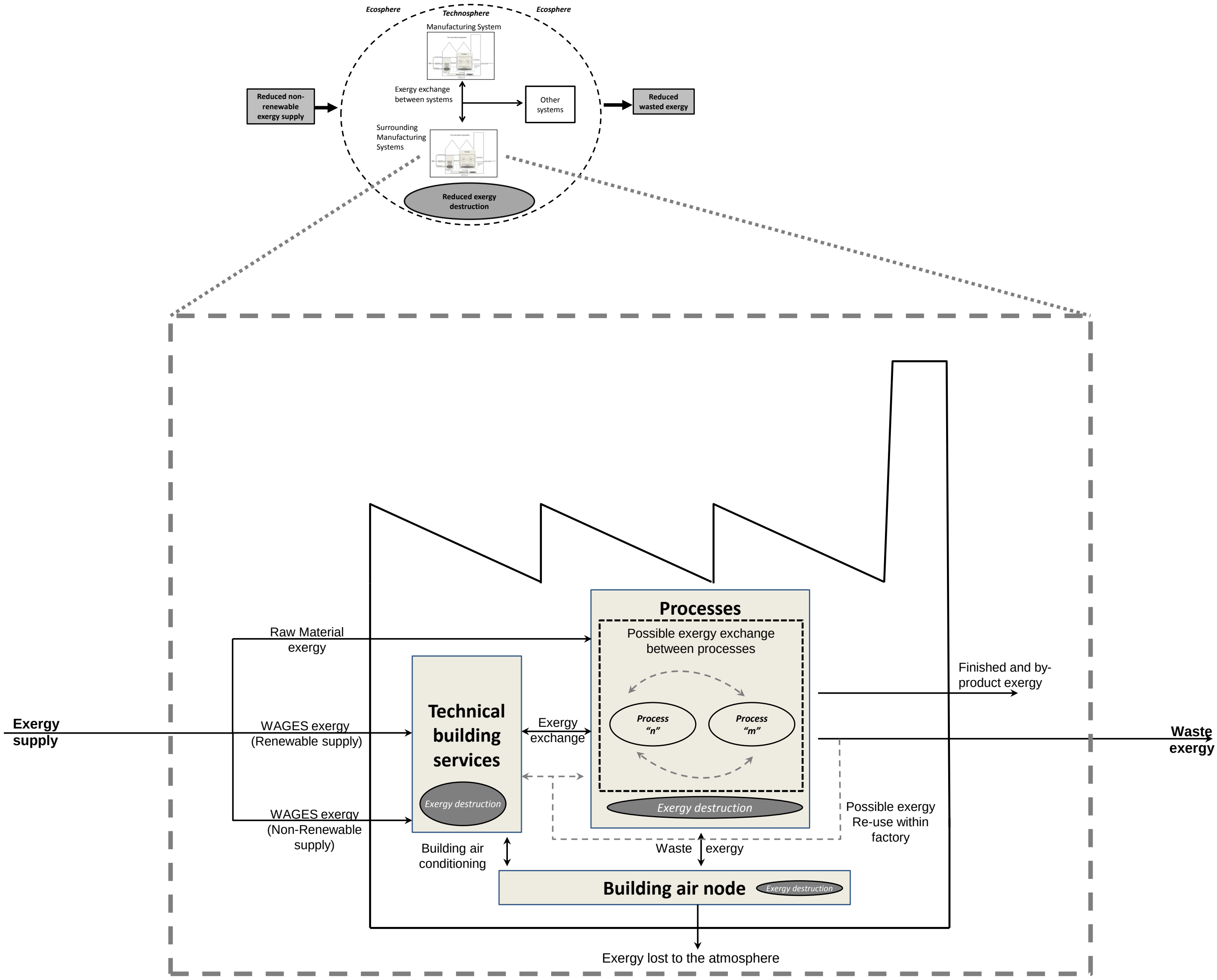

Figure 23 - A conceptual model for assessing and facilitating resource efficiency in a factory

A single building air node that is used to implement the exergy balance. In Figure 23 it is assumed that the generic factory consists of a single thermal zone. In practice, there may be multiple thermal zones with an equivalent number of zone air nodes that are also affected by radiation exchange. Therefore, the building air node in Figure 23 is a conceptual representation of all the thermal zones, including radiation exchange that may be present. Note that in an integrated system, the focus is on the performance of the whole system rather than its individual sub-systems. If synergies between sub-systems are to be developed, then the reduction of overall factory resource consumption should be viewed as the primary goal. If individual sub-systems are to be analysed, then their interactions with other systems of the factory need to be taken into account so that accurate results are generated.

The features of this approach are listed as follows,

- A generic manufacturing facility is modelled as an integrated system based on exergy flows;
- The bi-directional arrows between the sub-systems suggest possible reuse of exergy flows;
- The possibility of exergy reuse within the processes themselves is highlighted;
- A possible interchange of exergy between the sub-systems promotes a reduction in both exergy supplied and exergy wasted;
- Exergy destruction occurs within each sub-system of the factory. This indicates thermodynamic losses during resource transformations and represents loss of value;
- The supply exergy has both renewable and non-renewable components. This distinction is essential, since industrial sustainability depends on both increasing the proportion of renewable exergy supply and reducing exergy losses from the factory;
- At a larger scale, the factory can be considered one element of an industrial symbiosis network. In such a case, changes at an individual factory can be analysed for impacts on the resource efficiency of the whole network;

Despite its possible benefits, the analytical approach described has some drawbacks. Combining mass and energy flows into a common exergy flow adds to the complexity of the analysis, as the case studies in the following chapters illustrate. The effort needed to tackle the added complexity has to be justified if such an approach is to be implemented. Additionally, a complete holistic analysis would require data on all sub-systems of the factory. These are major challenges to the implementation of this approach in practice. In addition there are also theoretical inconsistencies in exergy calculations. For example, exergy analysis makes no distinction between flows that leave the factory that are beneficial and those that are harmful to the environment. Since both types of flow represent variations from the equilibrium state (Gaudreau et al., 2009), toxic waste flows will have positive exergy values, which represents a contradiction because useful value would be assigned to such flows. Furthermore, quantifying the chemical exergy of non-work producing substances such as minerals presents a challenge. A study by Delgado (2008) compared theoretically and experimentally obtained values of chemical exergy for minerals. A weak correlation between the two sets of results exposed this problem in exergy calculations. The issue of unresolved shortcomings in the theoretical basis of exergy analysis is also highlighted by Ao et al. (2008). While these issues of practice and theory detract from exergy analysis, significant advantages over energy analysis remain such as the ability to quantify natural resource consumption and facilitate improvement decisions. Its impact on decision making is particularly clear from the results of the case study in the following chapter.

Chapter 5

Case study 1 – An engine cylinder head production line

5.1. Introduction:

This chapter presents the first illustration of the novel conceptual model presented in the previous chapter. This is done through a case study of an engine cylinder head production line, the factory is analysed as an integrated system of production processes and the building, both interacting with each other to impact the resource consumption of its sub-components and the overall system. The following sections describe the manufacturing environment, and explain how the concepts in Chapter 4 can be applied in practice.

5.2. Case study description:

An engine cylinder head manufacturing line is studied that mainly involves metal cutting and washing processes. The factory's heating, ventilation and air conditioning (HVAC) system is an example of TBS (technical building services) that ensures comfortable working conditions inside the building. This study quantifies the non-renewable exergy supply and exergy destruction of a sub-component in the integrated factory environment, the HVAC system. Furthermore, the impact of heat reuse and the addition of photovoltaic generation are analysed.

In this analysis, changes to the HVAC system are considered following a holistic analysis of the production line and the building space. Figure 24 depicts the manufacturing system comprising three sub-systems: the HVAC as part of the TBS, the production line and the building. The resource efficiency is to be improved by considering three energy system options as shown in the figure. The baseline option considers the existing HVAC system with neither heat recovery nor renewable exergy supply. Option 1 incorporates a PV array, option 2 includes a heat recovery unit (HRU) and option 3 includes both the PV array and the HRU. The electrical exergy supplied by the PV that is surplus to the HVAC demand is used by the production line as shown in the figure. The HVAC system can be divided in two major subsystems:

- The dedicated outdoor air system (DOAS)
- A range of unit heaters (UH)

The DOAS is composed of an air handling unit (AHU) with supply and return fans, main heating coils (HC), a heat recovery unit subsystem (HRU) and an air distribution network. The system operates with 100% outdoor air. The air is distributed to the factory via 32 supply columns which each deliver around 1060 l/s (1.06 m^3/s) of a fresh air. In total 122,000 m^3/h (33.89 m^3/s) of fresh air is delivered to the factory. The main heating coils are controlled by the supply air temperature sensor which is set to a constant temperature of 17°C. The heat recovery effectiveness was set to a realistic 75%. Additionally, the UH subsystem is composed of 15 unit heaters, each with a heating coil and fan. A UH fan re-circulates room air and is switched off when there are no heating requirements. Each UH coil is controlled by a thermostat set to 21°C during occupied period. The set point during unoccupied periods (setback temperature) was unknown and was treated as a variable during calibration of the simulation model. The temperature profile for the hot water circuit, which delivers hot water from a heat source to heating coils (both in UH and AHU) was created using site data.

In the factory, only the overall electrical energy and heating energy usage were recorded and used to calibrate the baseline model. A computer model of the HVAC system was created using EnergyPlus (2012) and a simulation was performed to quantify the effects of changes to this system upon resource demand . Data for the building construction, lighting and production were acquired and input into the software model. The factory building energy model was created using the Legacy OpenStudio (2013) plugin. Data to configure the models were collected by factory visits and questionnaires to plant managers.

The factory is approximately 100m long and 56m wide, with average floor-to-ceiling height of 9.05m. Double-glazed units are installed on west, south and east facades and cover approximately 54.6m^2, 47.2m^2 and 39.8 m^2 of wall area respectively. The external wall is made of two layers of metal cladding (outer and inner) with a 100mm insulation layer and a 100mm concrete block layer. Construction data concerning the ground floor and roof have been selected according to the typical construction practice for this age (early 1980s) and building location. Table 6 shows the U-values of the most important construction elements and their composition.

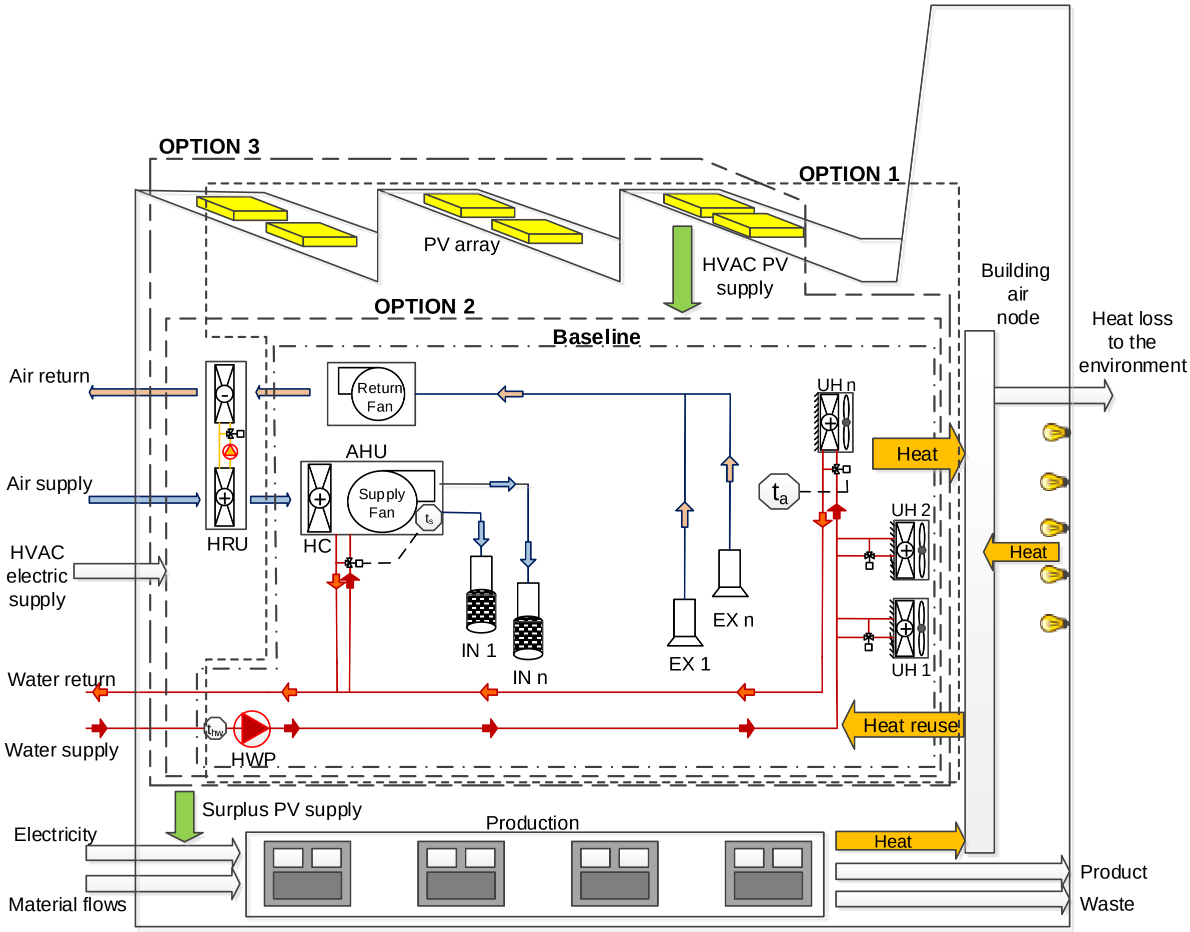

Figure 24 - The exergy based conceptual model illustrated for the automotive factory

72.5kW of artificial lighting is switched on for approximately 19.2 hours per day. The electricity consumption profile of the production lines has been derived from the measured electricity consumption which was then used to determine the internal gains from production equipment necessary for the HVAC modelling. It is assumed that only 30% of the heat from machining is dissipated as heat to surrounding air, while the rest is removed by other measures including the coolant system of the machining line.

Table 6 - Building model construction information

	Slab-on-ground Floor	Flat roof (no ceiling)	External wall	Glazing
U-value [W/m²K]	2.2	0.3	0.4	3.1
Outside layer	Floor insulation	19mm asphalt	White-painted steel	6mm clear glass
Layer 2	150mm concrete	13mm fibreboard	100mm concrete block	6mm air cavity
Layer 3	N/A	100mm insulation	100mm insulation	6mm clear glass
Layer 4	N/A	100mm concrete (light)	White-painted steel	N/A

Finally, a local weather file was used to drive the building energy model. To calibrate the model, two input variables were chosen. The first variable was the setback temperature set point and the second was the air infiltration rate. A range of values were assigned to each of these two variables. The calibration was setup in JEPlus (2013), a Java based EnergyPlus shell created to manage and run large and complex parametric simulations. The results from parametric simulations were used to calculate the root mean square error (RMSE) between the simulated heating demand and the real demand as measured by the factory's building management system (BMS). Values for the setback temperature set point and the air infiltration rate from the scenario with the lowest RMSE value of 90kW (which corresponded to the coefficient of determination of 0.62) were used for simulating the technology options considered in the study.

The building exergy analysis is based on the 'Low Ex' concept (Hepbasli, 2012) for building exergy management which focuses on matching the energy quality of supply and demand to reduce exergy losses and hence reduce natural resource consumption. As shown in Figure 25, the supplied building exergy is calculated in seven stages, starting from the primary energy transformation. Since the analysis approach presented here is confined to the factory, only the last three stages of the Low Ex approach are considered. The analysis of the HVAC system and the factory building in this study can therefore be considered the last three stages of the Low Ex approach (Khattak et al., 2014). The mass flow rates and temperatures calculated by the EnergyPlus hourly simulation are used to calculate the exergy flows. There are three type of flows involved in the factory for which exergy is calculated:

The electricity flow is pure work; therefore electrical energy and exergy are equal,

$$\dot{E}_{electrical} = \dot{Ex}_{elec}$$

The air involved is assumed to be an ideal gas. The exergy of air flows is therefore calculated as,

$$\dot{Ex}_{air} = \dot{m}_{air} c_{air} \left[(T - T_0) - T_0 ln \left(\frac{T}{T_0} \right) \right]$$

Where $\dot{m}_{air}$ $[kg/s]$ is the mass flow rate of the air; c_{air} $[kJ/kgK]$ is the specific heat capacity of air and T $[K]$ and T_0 $[K]$ are the air and outside temperatures respectively.

Finally, the water involved is assumed to be incompressible, the exergy being calculated as,

$$\dot{Ex}_{wa} = \dot{m}_{wa} c_{wa}\left[(T - T_0) - T_0 ln\left(\frac{T}{T_0}\right)\right]$$

The symbols $\dot{m}_{wa}$ $[kg/s]$ and c_{wa} $[kJ/kgK]$ are the mass flow rate and specific heat capacity of the water respectively.

These three exergy equations are sufficient to analyse all flows in the factory. Table 7 provides a sample calculation for the air and water flows through the unit heaters for 8 hours of production in January. The data show that as the streams flow, exergy from the water is transferred to the air.

Table 7 - Sample calculations for air and water flows through the unit heaters

Air						
Time	**Flow rate**	**Supply air Temp.**	**Exhaust air Temp.**	**Supply air Exergy rate**	**Exhaust air exergy rate**	**Air exergy gain rate**
(Hours)	kg/s	^oC	^oC	kW	kW	kW
1	0.00	14.41	14.41	0.00	0.00	0
2	0.00	14.33	14.33	0.00	0.00	0
3	19.48	17.35	22.72	4.95	10.23	5.28
4	40.31	20.00	26.51	16.48	32.98	16.5
5	40.31	20.00	26.33	16.35	32.29	15.94
6	40.31	20.00	26.31	16.70	32.71	16.01
7	40.31	20.00	26.23	16.44	32.11	15.67
8	40.31	20.00	26.11	16.19	31.41	15.22
Water						
Time	**Flow rate**	**Supply water Temp.**	**Return water Temp.**	**Supply water exergy rate**	**Return water exergy rate**	**Water exergy loss rate**
(Hours)	kg/s	^oC	^oC	kW	kW	kW
1	0.00	52.16	52.16	0.00	0.00	0
2	0.00	52.16	52.16	0.00	0.00	0
3	5.87	50.35	43.85	81.15	60.24	20.91
4	3.51	48.75	31.78	46.62	18.28	28.34
5	3.36	48.84	31.60	44.61	17.18	27.43
6	3.33	48.89	31.58	44.67	17.21	27.46
7	3.26	48.91	31.49	43.55	16.61	26.94
8	3.22	48.63	31.34	42.23	16.07	26.16

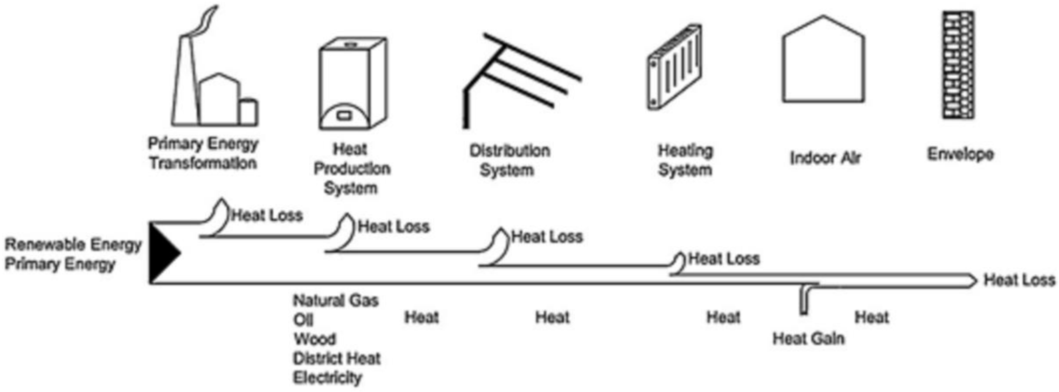

Figure 25 – Stages of energy flow transformations analysed in the LowEx approach (Hepbasli, 2012)

5.3. Baseline scenario

The baseline scenario against which improvement options will be compared considers the HVAC system without any heat recovery or renewable exergy supply. Since sustainability is linked to the consumption of non-renewable resources, the non-renewable exergy supplied is of concern. The rate of exergy supplied to the HVAC system and the rate of destruction of non-renewable exergy are calculated using the following equations:

$$\dot{Ex}_{supply} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{elec}$$

$$\dot{Ex}_{dest} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{in-air} + \dot{Ex}_{elec} - \dot{Ex}_{out-air}$$

The exergy rate delivered to the HVAC system from both the hot water flow and electricity are represented by $\Delta\dot{Ex}_{wa}$ $[kW]$ and $\dot{Ex}_{elec}$ $[kW]$ respectively. The supply cold air from outside the factory is at outside weather temperature, and therefore has zero exergy. The term $\dot{Ex}_{in-air}$ $[kW]$ is the supply air exergy rate to the unit heaters from within the factory space. Heat from the hot water is imparted to the inflowing air streams therefore delivering heated air to the building space ($\dot{Ex}_{out,air}$ $[kW]$).

5.4. Option 1 – With renewable exergy supplied from the PV array

In this scenario, renewable exergy is supplied to the HVAC system's electrical components as energy from a PV array ($\dot{Ex}_{PV,HVAC}$ $[kW]$). Since electricity is work (by definition), the non-renewable exergy supplied and exergy destroyed are calculated using the following equations:

$$\dot{Ex}_{supply} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{elec} - \dot{Ex}_{PV,HVAC}$$

$$\dot{Ex}_{dest} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{in-air} + \dot{Ex}_{elec} - \dot{Ex}_{PV,HVAC} - \dot{Ex}_{out-air}$$

5.5. Option 2 – With heat recovery

This option considers reuse of heat from the factory building space. Air from the building space is extracted by the HVAC air extraction system and used to preheat incoming cold air from the outside in a heat recovery unit (HRU). The mass and energy flow data are used to establish the exergy balance. The exergy supply rate and exergy destruction rate are calculated using the equations below:

$$\dot{Ex}_{supply} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{elec}$$

$$\dot{Ex}_{dest} = \Delta\dot{Ex}_{wa} + \dot{Ex}_{elec} + \dot{Ex}_{in-air} + \dot{Ex}_{recov} - \dot{Ex}_{out-air}$$

The rate of exergy delivery to the HVAC system from both the hot water flow and electrical supply are represented by $\Delta\dot{Ex}_{wa}\ [kW]$ and $\dot{Ex}_{elec}\ [kW]$ respectively. To calculate the exergy destruction rate, the exergy delivered to the HVAC system from heat recovery ($\dot{Ex}_{recov}\ [kW]$) must be quantified. Even though the internal gains from the production and building space are not direct inputs to the HVAC system, heat from these sub-systems is imparted to the TBS sub-system (in this case the HVAC system) through the heat recovery process. It was therefore necessary to quantify these gains, which was done using the simulation approach described earlier.

5.6. Option 3 – With heat recovery and solar power

The final option incorporates both the PV array and the HRU into the factory energy system. The size of the roof PV plant was determined by conducting a multi-objective optimisation study with two objectives; to maximise total annual PV plant electricity generation and minimise payback period. Parameters which were varied in the optimisation study were (i) PV panels slope angle, (ii) PV panel size orientation (horizontal or vertical), (iii) number of PV arrays and (iv) distance between PV arrays. The selected optimal solution has less than 10 years payback period based on an assumed investment cost of 1,200 Euros per kW of installed power. This calculation was based on data from the UK Department of Energy and Climate Change (DECC, 2012), and the factory electricity cost of 0.1 Euro per kWh. Since one objective is a reduction in destroyed exergy, a match is sought between the energy quality of supply and demand. For this reason the PV supply should fulfil only electrical demand and not heat demand (for example). The non-renewable exergy supply is therefore given as:

$$\dot{Ex}_{supply} = \Delta\dot{Ex}_{wa} + \left(\dot{Ex}_{elec} - \dot{Ex}_{PV,HVAC}\right)$$

In order to quantify the destruction of non-renewable exergy, the exergy balance for the HVAC system is established. The basic exergy balance for any system is given as:

$$\dot{Ex}_{in} = \dot{Ex}_{out} + \dot{Ex}_{dest}$$

Where $\dot{Ex}_{in}$ $[kW]$ and $\dot{Ex}_{out}$ $[kW]$ is the non-renewable exergy entering and leaving the system respectively. Figure 26 shows the exergy flows through the HVAC system in option 3. The reuse of exergy forms a circular loop as shown in the diagram. The figure shows two sources of thermal exergy to heat the incoming outside air - warm air from the factory space and heat from water flowing through the system. Additionally, the factory space air is heated by the HVAC system itself and internal gains from within the factory building. The factory workforce, artificial lighting and production equipment are the sources of internal gains, but since the contribution of the workforce is negligible, it is neglected. Since a part of the supply to the production machines and lighting is from the PV array, a portion of the thermal exergy in the factory air is thus supplied from a renewable source. This is also true for the heat recovered as it is also extracted from factory air. Let φ represent this proportion of renewable sourced thermal exergy in the factory air where,

$$\varphi = \frac{\dot{Ex}_{PV}}{\dot{Ex}_{total\ elec}} \times \frac{\dot{Ex}_{gains}}{\Delta\dot{Ex}_{wa} + \dot{Ex}_{gains}}$$

In order to separate out the renewable sourced exergy in the outgoing flow of warm air, let σ represent the proportion of the air exergy in the total that enters the HVAC system. It is given as,

$$\sigma = \frac{\dot{Ex}_{in-air} + \dot{Ex}_{recov}}{\dot{Ex}_{wa} + \dot{Ex}_{in-air} + \dot{Ex}_{recov}}$$

It follows that the fraction of renewable sourced exergy in the total that enters the HVAC system is given by the product "$\varphi\sigma$". The exergy balance for non-renewable exergy flow through the HVAC system with heat recovery and solar power supply is given as follows.

$$\dot{Ex}_{supply} + (1-\varphi)\dot{Ex}_{in-air} + (1-\varphi)\dot{Ex}_{recov} = \dot{Ex}_{out-air}(1-\varphi\sigma) + \dot{Ex}_{dest}$$

It should be noted here that there is no physical distinction between the destruction of renewable and non-renewable sourced exergy. However, this parameter is required in order to quantify the losses of non-renewable exergy from the system.

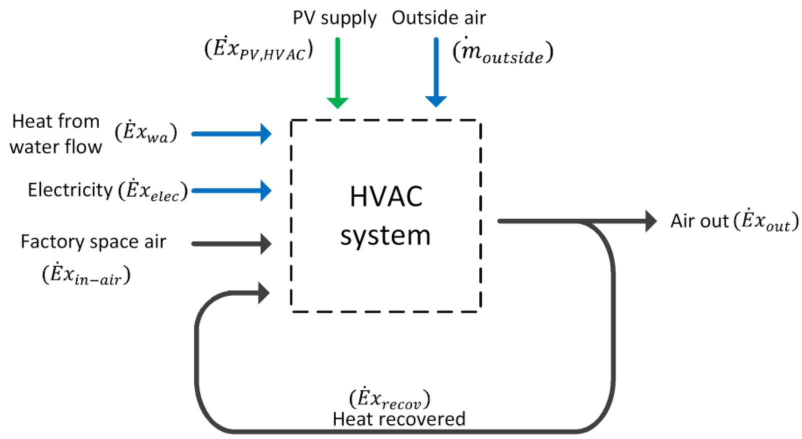

Figure 26 - Flows through the HVAC system in option 3

5.7. Results:

Based on hourly values, the exergy supply rate for the three cases is shown in Figure 27**Error! Reference source not found.**. It can be seen that the non-renewable exergy supply progressively reduces as one considers manufacturing system options from the baseline to option 3. For the baseline, the non-renewable exergy supplied is 852MWh/year which reduces to 646 MWh/year for the option with PV only and 628 MWh/year for the option with heat recovery only. Finally, the system with heat recovery and solar power requires the least amount which is 412 MWh of non-renewable exergy per year.

A similar pattern of reduction was also observed for non-renewable exergy destruction. For the baseline, it was 711 MWh/year which reduced to 526MWh/year for the option with solar power only and 581 MWh/year for the option with heat recovery only. Finally, the system with heat recovery and solar power had the lowest non-renewable exergy destruction of 361MWh/year.

When looking at weekly trends, for a short period around July and August, the PV array generates more electricity than is required for production and the factory lighting and HVAC system. Figure 28 shows the PV generated power and the total electric power demand of the factory averaged over a week. The surplus solar exergy using weekly values amounts to 82 MWh/year. However, if hourly values are considered, the PV array provides a surplus electricity of 185 MWh through the year. This is because that solar power is highly variable and using average values significantly affects the accuracy of the results.

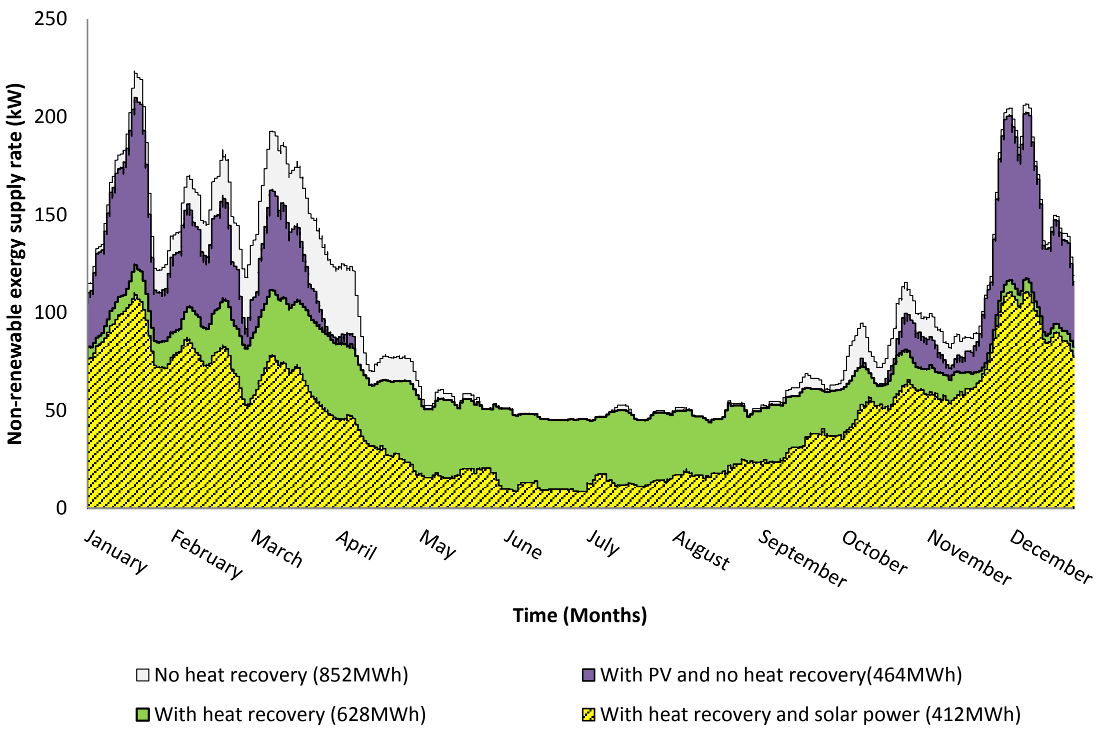

Figure 27 - Non-renewable exergy supply comparison

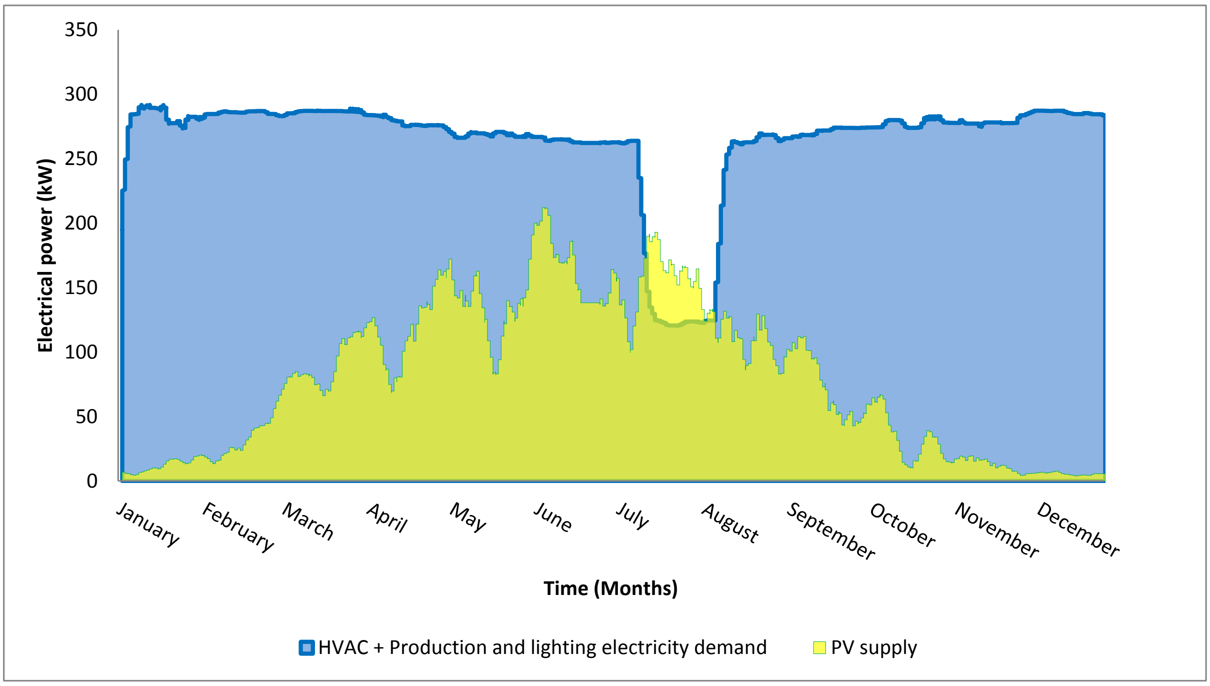

Figure 28 - PV supply and electricity total demand of the factory

For all three options, the yearly non-renewable energy and non-renewable exergy supplies are tabulated in Table 8 along with the non-renewable exergy destruction, showing percentage reductions in both.

	Non-renewable energy supply (MWh/year)	**Non-renewable exergy supply (MWh/year)**	**Non-renewable exergy destruction (MWh/year)**
Baseline system	2962	852	711
Option 1 – PV only	2756	646	526
Option 2 – Heat recovery only	1333	628	581
Option 3 – Heat recovery & PV	1118	412	361
Reduction from Baseline in Option 1	206 (6.9%)	206 (24.2%)	185 (26%)
Reduction from Baseline in Option 2	1634 (55%)	224 (26.2%)	130 (18.2%)
Reduction from Baseline in Option 3	1849 (62.3%)	440 (51.6%)	350 (49.2%)

Table 8 - Results summary table

The percentage reduction is important when selecting the most resource efficient technology option for the HVAC system. Therefore, Figure 29 graphically presents the absolute values as well as percentage reductions from the baseline for each technology option. The energy supply is reduced by 7% from the baseline when only PV supply is employed. A much bigger reduction of 55% of baseline energy results from the heat recovery option. For this reason, in option three where both the PV supply and heat recovery are employed, there is 62.3% reduction from the baseline.

The exergy supply comparison gives very different results from that derived from energy analysis. The exergy supplied reduces by 24% and 26% respectively for the PV array and heat recovery options. This means that based on the exergy approach, both these technology options have similar benefits with respect to resource efficiency. Consequently, for the third option when both the PV and heat recovery are employed, there is a total reduction in exergy supply of 52%.

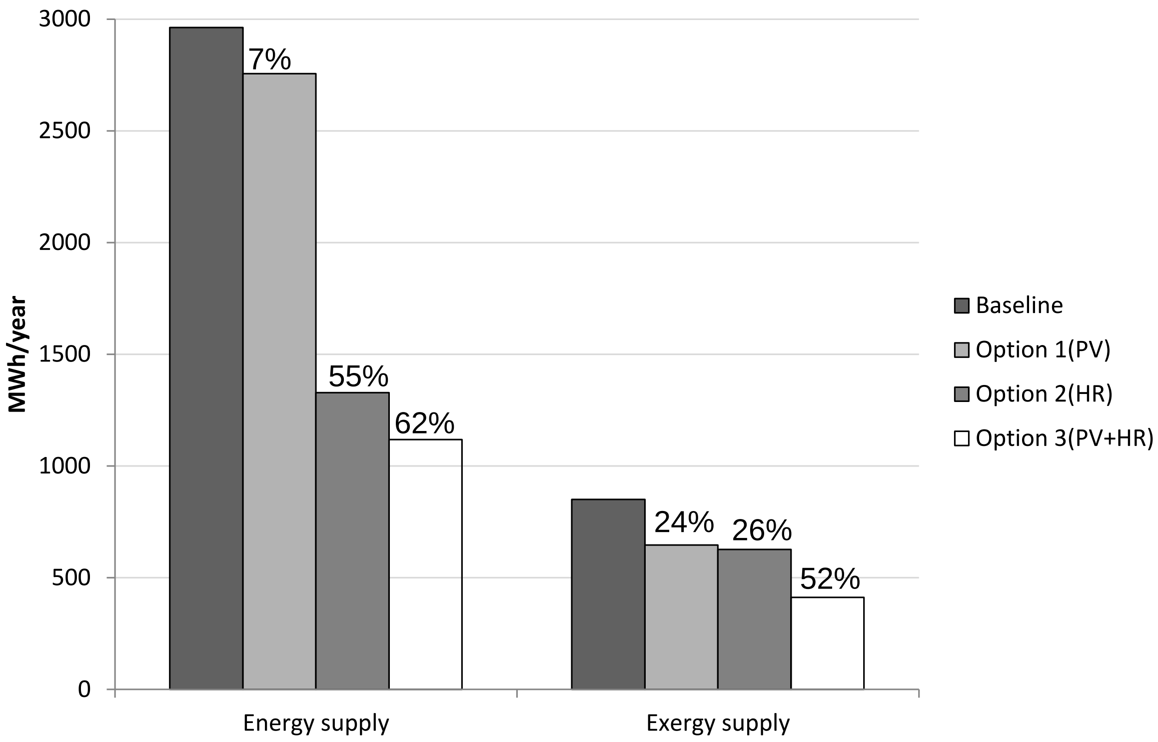

Figure 29 – Comparison of reductions in energy and exergy supply

5.8. Discussion:

In this chapter, the novel conceptual approach previously presented in chapter 4 was illustrated through a case study. The non-renewable exergy supply and exergy destruction were the parameters used to quantify the resource efficiency of the system. The issues encountered in deploying the approach in practice and the results are now discussed.

Compared to an energy analysis, the exergy analysis required no extra data for the HVAC system. Figure 24 however shows that data relating to systems external to the HVAC system (in this case production machinery and lighting) are required. In addition, an artificial distinction has to be made between renewable and non-renewable exergy, for the flows leaving the systems. This is demonstrated in option 3 where the heat delivered by the HVAC is separated into renewable and non-renewable portions. Table 8 provides a summary of the results for the three technology options considered. The destruction of exergy from non-renewable sources is reduced by 49.2% of the baseline using option 3, whereas the non-renewable exergy supply is reduced by 51.6%.

Compared to results based on energy analysis, option 3 represents a reduction of non-renewable energy supply by 62.3% of the baseline, indicating more significant resource savings compared to the results of exergy analysis. This can be attributed to the fact that energy analysis does not distinguish between reductions of thermal energy and electrical energy. However, these two energy streams have different work potential, usefulness and consequently value to society. Energy analysis therefore exaggerates resource efficiency results. This shortcoming is further exposed when comparing the technology options for reducing non-renewable energy supply. In Figure 29, it is clear that according to the energy analysis, the reduction in non-renewable energy supplied is much smaller using the PV array than that achieved using the heat recovery unit. Note that the energy approach considers a kilowatt of thermal energy in water at 60^{o}C to be equivalent to a kilowatt of electrical energy, although the useful work potential of electrical energy is greater than that of hot water with the same energy content, so a comparison between the two technologies on the basis of energy savings is inadequate for resource efficiency purposes. Such a comparison might suggest to decision makers that employing a heat recovery unit only is the most effective technology option. The exergy approach however yields different results, as Figure 29 show that both the PV and heat recovery unit are equally effective in improving resource efficiency. The results from the exergy approach suggest that incorporating both the PV and heat recovery may be the best option. Table 28 shows the non-renewable exergy supply throughout the year. The profile is based on hourly values that are averaged over a week. It can be seen that the effect of heat recovery is more significant in winter (as one would expect). The reuse of heat from factory air is a particularly effective use of low grade thermal energy. By recovering the heat in the factory air to preheat very cold incoming air from outside, a low energy quality demand is fulfilled by a low energy quality supply. In other words, a low exergy demand is being met by a low exergy supply. Matching of energy quality between supply and demand reduces exergy destruction. Considering that the destruction of non-renewable exergy ranges from 83.5% to 92.5% of that supplied, energy quality matching can be seen to have a major impact on resource efficiency. On a similar note, the surplus electricity generated by the PV (185MWh/year) should only be used to meet demand for electrical energy. If it is used to fulfil demand for low quality energy (for example, heat) within the factory, the accompanying increased exergy destruction would significantly reduce resource efficiency. Therefore, the conceptual approach presented suggests exporting the surplus PV supply once all electrical demand within the factory is met.

Finally, option 3 is not the last word in resource efficiency. Further actions might be explored using the suggested approach, both inside or outside the factory. For example, the HVAC resource consumption could be further reduced via an exergy interaction with the production line. An example would be reusing surplus heat in the waste water from the washing processes to preheat the incoming outside air. Taking an integrated approach to factory analysis thus allows one to see further opportunities for improvement. Additionally, the use of the 2nd law in the approach provides a strong base for resource accounting. Both these factors combined demonstrate how this approach to resource efficiency can be a useful decision making tool for industrial sustainability. The conclusions drawn from the study, and the findings generated will be discussed in conjunction with the other two case studies in chapter 9.

Chapter 6
Case study 2 – A jaggery production process

6.1. Introduction:

While Chapter 5 presented the illustration of the resource accounting approach at the factory level, this chapter will show how it could be used at a higher level of aggregation. This is done through the case study of a production process for jaggery (a sugar product). The exergy analysis of a jaggery production furnace is conducted, thus allowing calculating the exergy destruction and wasted exergy. Since the jaggery furnace was supplied by bagasse, a renewable fuel, this is essentially a study of a furnace fired by renewable fuel. In view of the conceptual approach (repeated here for convenience), renewable supply should be used as efficiently as possible, measured through exergy destruction and exergy efficiency.

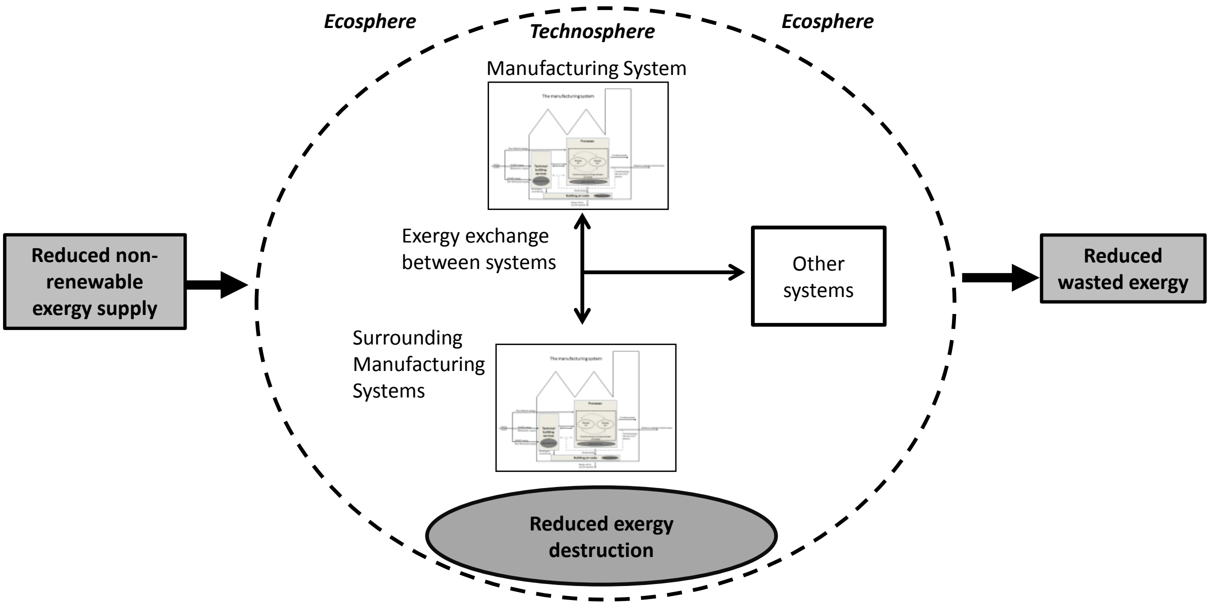

Figure 30 - An industrial ecology and exergy based model for resource accounting in manufacturing

The process studied is an individual process that operates independently where significant exergy is expelled to the environment and lost as waste heat. In order to understand the effect of waste heat reuse upon resource consumption, the potential for industrial symbiosis is explored by imagining a hypothetical secondary process that is able to use the wasted exergy. Industrial symbiosis (IS) is a useful concept that exploits synergies between individual systems to reduce the resource consumption in the linked systems. Additionally, exergy can be a useful tool in assessing the identified synergies, since all mass and energy flows can be translated into common physical units. Therefore, the exergy concept is used to measure resource consumption in an industrial symbiosis system, thus illustrating the conceptual approach of Figure 30.

The following section describes briefly the concepts of industrial ecology and industrial symbiosis, and explains why exergy can be useful in analysing such systems.

6.2. Industrial symbiosis, industrial ecology and exergy

The term ‘industrial symbiosis’ is used to describe a collection of industrial systems that exchange energy and material with each other to maximize resource efficiency. The theoretical basis is explained by Ayres (1988) who proposed the term ’industrial metabolism’, which referred to a physical process or a collection of processes that converted raw material, energy and labour into finished products and wastes. In practice, the first industrial symbiosis that conformed to the ideas of Ayres and Simonis (1994) was reported in Kalundborg, Denmark (Jacobsen, 2006). The Kalundborg industrial park was presented as an example in which different industrial actors cooperated to reduce supplied and wasted resources; this phenomenon was termed ‘industrial symbiosis’ (IS). Many examples of IS have since been implemented around the world (Lombardi and Laybourn, 2006). Industrial symbiosis can be considered the main part of a broader concept called industrial ecology (IE). Industrial ecology may be defined as the study of interactions both within industrial systems and between industrial and natural systems (Erkman, 1997). Its key feature is that of regarding a collection of industrial systems as an ecosystem, in order to reduce supply and waste of resources. The objective is to shift linear operations to cyclical ones, thus forming reuse loops to maximize efficiency.

Since the goal of IS or more broadly, IE is the maximization of resource efficiency, it is important to quantify the resource flows using suitable metrics. The lack of metrics to quantify the benefits of IS was reported as a knowledge gap in a report for the UK by Lombardi and Laybourn (2006). Most of the methodologies currently employed to assess IS and IE in practice are based on accounting of mass and energy flows separately (Zhang et al., 2014), analyses which have their roots in the 1st law of thermodynamics. Since energy possesses both quantity and quality, assessing reuse opportunities without considering its quality may not be the best approach to industrial symbiosis.

A review of IS theory and methodologies by Zhang et al. (2014) identified knowledge gaps in this area of science. The lack of flexible approaches that can account for the variety of flows in an industrial complex was identified. More flexible approaches would allow a holistic understanding of the internal processes as well as exchange of resources within a large complex system. The most widely used analysis tool in industrial symbiosis is input-output analysis (Miller and Blair, 2009). This is a powerful methodology but has a drawback of using different measurement units for the different flows. This disadvantage is overcome by using monetary cost, which introduces a degree of subjectivity to the analysis.

A focus on exergy, a non-conserved quantity, is perhaps better suited to assessing IS systems. A distinct advantage of using the exergy concept is allowing the analyst to model both mass and energy flows in the same physical units while taking into account their quality in addition to quantity. Therefore, the use of the exergy concept in accounting methods could address the lack of flexibility in dealing with the variety of flows in IS systems as identified by Zhang et al. (2014). Additionally, modelling all flows in common units would facilitate a holistic understanding of resource reuse opportunities without introducing subjectivity. Consequently, it has been considered a suitable quantitative basis for IE and resource accounting, as argued by Wall and Gong (2001b), and Seager and Theis (2002). For example, Valero et al. (2012) conducted the first exergy analysis of the Kalundborg eco-industrial park in which the benefits of system integration were quantified using exergy.

The remaining chapter describes the case study, and details how the exergy analysis was carried out for two operating conditions. Section 6.9 specifically explores how the two operating conditions might impact resource consumption in the integrated IS system. The benefits or drawbacks of using the exergy-based approach and its impact on decision making regarding the symbiosis are discussed. Finally, insights gained from energy and exergy analyses are compared in order to understand whether the exergy-based approach has any benefits to offer.

6.3. Case study methodology

Sardeshpande et al. (2010) described the optimization of a process for manufacturing 'jaggery' (a sugar substitute) using energy analysis to identify advantageous changes that could be made to the basic process. Using an experimental approach, an alternative fuel feed rate was implemented in order to improve the energy efficiency. The energy efficiency and specific energy consumption of the process were previously calculated based on measured data.

This current study extends the previous work by conducting an exergy analysis of the process based on the mass and energy flow data collected by Sardeshpande et al. (2010). Exergy flows for the baseline and modified scenario are calculated and the exergy efficiency and exergy destruction is quantified. Unless otherwise stated, the chemical exergy values of the elements and compounds in the analysis are taken from CIRCE (2008). The integration of the jaggery process with a hypothetical symbiotic process is considered for the two scenarios, thus quantifying the impact of individual process changes on the overall system. It is important to note here that this study is not intended to present the thermal optimization of a jaggery furnace using exergy, rather the goal is the presentation of how an IS system, could be modelled in terms of exergy thus illustrating the conceptual approach.

6.4. Jaggery production case study

Jaggery is a sugar-cane based product used as a substitute for sugar. The case study presented here is based on a processing plant in India. Jaggery has been produced for centuries and its production today constitutes 20% of the sugar-cane industry in India. The jaggery production process involves extracting juice from the sugar-cane using a crushing machine. The juice is then transported via a conveyer to a set of pans. The juice in the pans is continuously stirred while being heated by a furnace up to a required temperature. The juice is thickened as water is driven off until it reaches the required specification when it is cooled and finally solidifies in moulds, see Figure 31.

The instrumentation used by Sardeshpande et al. (2010) to acquire the experimental data for the previously conducted energy analysis is listed in Table 9. Based on an energy analysis of the system, operational modifications were made to improve the system performance by ensuring complete combustion within the furnace. The main modifications made to the baseline scenario were shifting to a more controlled fuel feed rate and lowering the operating temperature of the furnace. While the mass and energy balances were established in the previous study, this paper implements an exergy balance for the jaggery process.

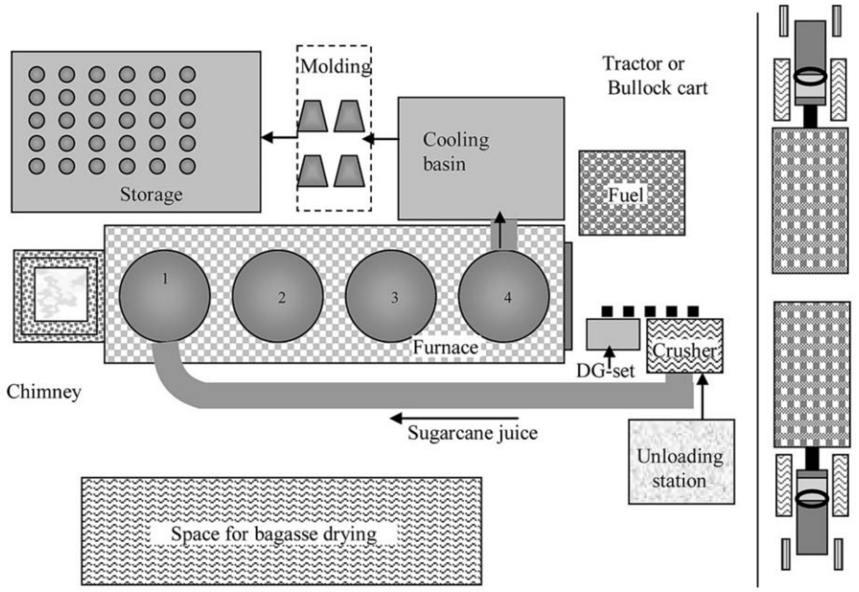

Figure 31 – Jaggery processing setup (Sardeshpande et al., 2010)

List of instruments used for measurement

Instrument	**Specification**
Weighing balance	Range: 0.25-20kg Least count: 50g
Stop watch	Least count: 1s
High temperature sensor	Range: 0-1200C
K-type thermocouple	Least count: 1C
RTD for ambient temperature measurement	Range: 0-200C Least count: 0.1C
Dry flue gas analyser for oxygen (O_2) and carbon monoxide (CO) sensing	Range: 0-21% O_2 and 0-20,000ppm CO Least count: 0.1 O_2 and 1ppm CO

Table 9- measurement instrumentation (Sardeshpande et al., 2010)

6.5. System analysis

In order to establish the mass, energy and exergy balances, a control volume approach has been taken. The evaporation of water from the juice is the core of the process, and this is accomplished in a bagasse fired furnace. The skin of the sugar-cane left after crushing is called bagasse and serves as renewable fuel for the furnace. Before the bagasse can be used, it needs to be dried. Depending upon the recipe, small amounts of chemical additives (such as lime and okra juice) are added to the cane juice to purify it. Figure 32 depicts the control volume of the jaggery furnace which shows all the material and energy flows, where steady flow is assumed.

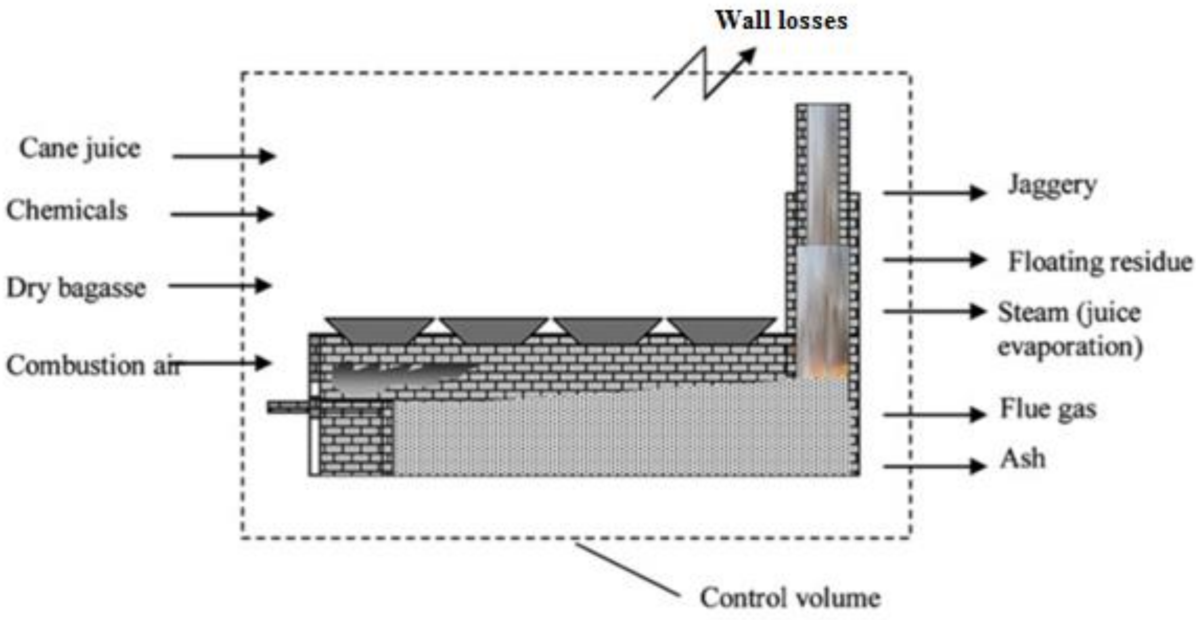

Figure 32 - Jaggery furnace control volume, adapted from (Sardeshpande et al., 2010)

The mass balance is a pre-requisite to establishing the energy balance. The mass balance accounts for flows which would have been difficult to measure. Based on Figure 32, the mass balance in terms of the absolute amounts of masses used per day is as follows,

Mass of juice + Mass of bagasse + Mass of combustion air + Mass of chemicals and okra = Mass of flue gas + Mass of jaggery + Mass of water evaporated + Mass of ash + Mass of floating residue

$$m_{juice} + m_{bagasse} + m_{air} + m_{chemical\,\&\,okra} = m_{flue} + m_{jaggery} + m_{steam} + m_{ash} + m_{fr}$$

6.6. Energy analysis

From the flows in Figure 32, the energy balance is established as follows,

Energy rate from bagasse = Energy rate for sensible heating of juice + Energy rate for juice evaporation + Energy rate in liquid jaggery + Energy rate carried in flue gas + Energy rate from wall losses + Energy rate lost from ash + Energy rate lost in un-burnt fuel

$$\dot{E}_{bagasse} = \dot{E}_{pre-heat} + \dot{E}_{evap} + \dot{E}_{jaggery} + \dot{E}_{flue} + \dot{E}_{wall\ losses} + \dot{E}_{ash} + \dot{E}_{unburnt}$$

From the energy balance, the energy efficiency of the combustion process can be calculated. The efficiency of a process is useful in assessing its performance and is the ratio of the useful output to the supplied input. It is calculated as,

$$\eta_{energy} = \frac{\dot{E}_{jaggery} + \dot{E}_{evap} + \dot{E}_{pre-heat}}{\dot{E}_{bagasse}}$$

Where the energy used for preheating is the sensible heating of the cane juice up to the boiling point. $\dot{E}_{evaporation}$ is the energy rate used during evaporation and $\dot{E}_{jaggery}$ is the heat carried away by the finished product. Even though all of the latent heat of evaporation and part of the preheat energy is lost from the system, it directly contributes towards the useful product and is therefore considered a useful output energy flow. The mass and energy balances are described in further detail in Sardeshpande et al. (2010).

6.7. Exergy balance

While energy efficiency is a measure of performance, it does not give any indication of the degradation of resource quality, whereas exergy analysis can overcome this shortcoming. Unlike energy, exergy is not a conserved quantity. When setting up an exergy balance there is a portion that is destroyed, which is caused by the irreversibility of real thermodynamic processes. The loss of exergy as resources flow can be considered to be indicator of resource consumption and is a quantity of interest in this analysis. The general exergy balance for a steady state system is as follows,

$$\dot{Ex}_{in} = \dot{Ex}_{out} + \dot{Ex}_{dest}$$

The exergy balance for the mass and energy flows in Figure 32 is given as,

$$\dot{Ex}_{juice} + \dot{Ex}_{bagasse} + \dot{Ex}_{air} + \dot{Ex}_{chemicals}$$

$$= \dot{Ex}_{jaggery} + \dot{Ex}_{flue} + \dot{Ex}_{wall-\ losses} + \dot{Ex}_{ash} + \dot{Ex}_{vapour} + \dot{Ex}_{fr} + \dot{Ex}_{dest}$$

The mass of chemicals and okra juice are 0.04% each per kilogram of product. The chemicals are calcium carbonate and phosphoric acid with specific chemical exergies of approximately 18kJ/mol 107kJ/mol respectively. Okra juice is mainly composed of protein, fat, sugar and moisture (Adelakun et al., 2009). Since both the quantity and the specific chemical exergy of the chemicals and okra is only a small fraction of the cane juice and bagasse, the chemical exergies of these input streams can be safely neglected. Similarly, on the output side, the floating residue is 1.5% by mass of the cane-juice at the point at which it is skimmed off. The floating residue being composed of sand and bagasse fibres, its small quantity allows one to safely neglect the exergy associated with this stream. Finally, the air used in the combustion process is fresh air from the reference environment, which therefore has zero exergy by convention. The simplified balance is then as follows,

$$\dot{Ex}_{juice} + \dot{Ex}_{bagasse} = \dot{Ex}_{jaggery} + \dot{Ex}_{flue} + \dot{Ex}_{wall\,losses} + \dot{Ex}_{ash} + \dot{Ex}_{vapour} + \dot{Ex}_{dest}$$

The performance indicator, exergy efficiency is defined as,

$$\eta_{exergy} = \frac{\dot{Ex}_{jaggery} + \dot{Ex}_{vapour}}{\dot{Ex}_{bagasse}}$$

Where $\dot{Ex}_{jaggery}$ is the exergy rate of the jaggery, $\dot{Ex}_{vapour}$ is the exergy rate carried away by the water vapour leaving the system and $\dot{Ex}_{bagasse}$ is the supplied exergy rate of bagasse for combustion. The exergy balance is composed of a variety of mass and energy flows. The calculation of each term is described now.

A classification of different types of exergy has been given by Gundersen (2009) and is depicted in Figure 33. Further detail about exergy and its application to manufacturing processes can be found in (Bejan, 1988; Dincer and Rosen, 2012; Khattak et al., 2012; Sciubba and Wall, 2010). The calculation method for each term in the exergy balance corresponding to their respective exergy flows will now be explained. All values of specific chemical exergy are taken from CIRCE (2008) unless otherwise stated.

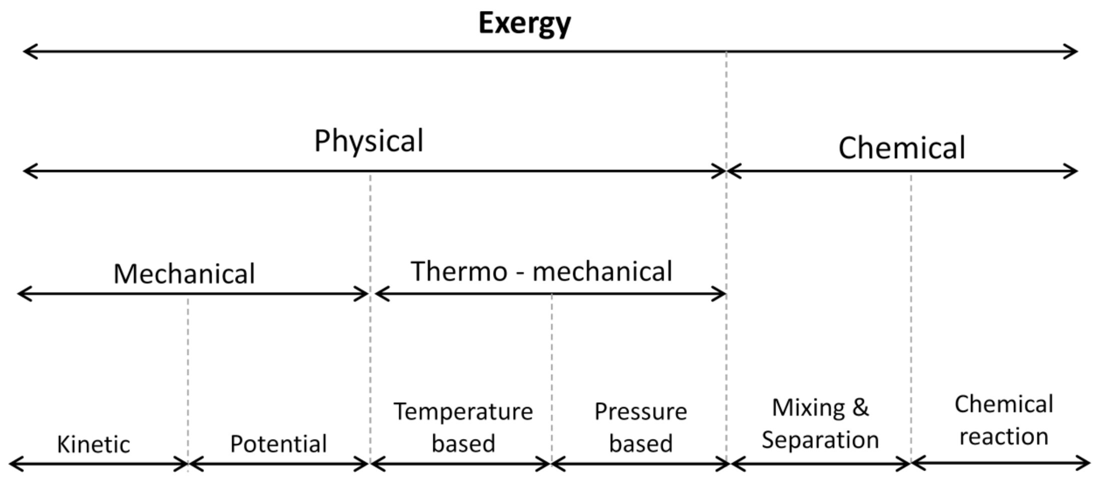

Figure 33 - Classification of exergy types Gundersen (2009)

6.7.1. Specific exergy of sugar cane juice

After crushing the sugar cane, the juice is separated out that is the raw material for the process. Figure 33 shows that the total exergy of any mass flow is composed of six parts. For the cane juice flowing at ambient conditions, the physical exergy is negligible and the chemical exergy needs to be calculated. Approximately 85% of the solute is sucrose while there are numerous other carbohydrates, salts and minerals present in minute quantities (Walford, 1996). However for simplicity, it is assumed that the cane juice is a solution of only sucrose in water. Additionally, it is assumed that the water is at the condition of the water present in the reference environment, therefore it has zero exergy. This simplification is reasonable since the specific exergy of water calculated by rather complex methods (B. Chen et al., 2009) is negligible compared to that of sucrose (Tai et al., 1986). The chemical composition of sucrose is $C_{12}H_{22}O_{11}$ with a specific chemical exergy of 5969.28kJ/mol or 17.45 MJ/kg (Tai et al., 1986). The cane juice in this case study was measured to have a specific gravity of 18 degrees Brix, meaning that 100g of solution contained 18g of sucrose so that the composition of the cane juice was 18% sucrose. The specific exergy of the sugar cane juice flow is therefore 3141kJ/kg.

6.7.2. Specific exergy of bagasse

The chemical exergy (ε_0) of the wet bagasse is calculated through the method proposed by Kamate and Gangavati (2009)

$$\varepsilon_0 = \left[(NCV)_0 + wh_{fg}\right]\emptyset_{dry}$$

Where, NCV is the net calorific value, $\emptyset_{dry}$ and w are the ratio of the chemical exergy to the net calorific value of the fuel and fraction of moisture in bagasse respectively. The value of $\emptyset_{dry}$ depends on the composition of carbon, oxygen and hydrogen in the bagasse and is calculated as,

$$\emptyset_{dry} = \frac{1.0438 + 0.1882\left(\frac{h}{c}\right) - 0.2509\left[1 + 0.7256\left(\frac{h}{c}\right)\right] + 0.0383\left(\frac{n}{c}\right)}{1 - 0.3035\left(\frac{o}{c}\right)}$$

The ultimate analysis of the bagasse revealed the moisture to be ranging from 8-10%. Therefore the specific chemical exergy of the bagasse for 9% moisture content is calculated to be 13.2 MJ/kg. It should be noted here that bagasse is considered a renewable exergy source (Contreras et al., 2009; Moya et al., 2013).

6.7.3. Specific exergy of the jaggery produced

The jaggery produced is measured to have a specific gravity of 85 degrees Brix. Therefore the makeup of jaggery is 85% sugars and 15% moisture. The composition of the sugars in jaggery has previously been quantified in studies by (Rao et al., 2007; Singh et al., 2013). Upon heating the cane juice, a part of the sucrose is converted to glucose and fructose. Both of these sugars have the same chemical formula ($C_6H_{12}O_6$) and therefore have the same specific chemical exergy of 2975.85 kJ/mol or 16.5 MJ/kg (Tai et al., 1986). In view of the values of mass flow rate and temperature at which the jaggery is produced; the thermo-mechanical, kinetic and potential exergy can be safely neglected. The total specific exergy of the jaggery is therefore 14025kJ/kg.

6.7.4. Specific exergy of the water vapour

The exergy of the water vapour that leaves the system as a result of heating the cane juice is calculated as,

$$\dot{Ex}_{vapour} = \dot{m}_{vapour}[(h - h_0) - T_0(s - s_0)]$$

The enthalpy and entropy values are taken from steam tables; the specific exergy of the vapour leaving the system is calculated to be 488.4kJ/kg.

6.7.5. Exergy of the flue gas

The flue gas can be assumed to be an ideal gas with its constituents being the combustion products, CO_2, H_2O and N_2. The exergy of this flow is comprised of the thermo-mechanical and chemical parts. Taking into account the specific chemical exergy (CIRCE, 2008) and the mass flow rate of the flue gas, the chemical exergy of H_2O and N_2 can be neglected. The total exergy of the flue gas is calculated as follows,

$$\dot{Ex}_{flue} = \dot{m}_{flue\ gas}\left[C_p\left(T_{flue} - T_0\right) - C_p T_0\left(\ln\frac{T_{flue}}{T_0}\right)\right] + Ex_{ch,CO_2}$$

It is important to keep the chemical exergy of the CO_2 $(445.5kJ/kg)$ separate from the thermo-mechanical part as it may not be usable by a secondary process and maybe considered as transiting exergy for the secondary process if that is the case (Kellens et al., 2011b).

6.7.6. Specific exergy of bagasse ash

Bagasse ash composition, dominated by SiO_2 was given by Cordeiro et al. (2004) and is shown in Table 10. Considering the top five compounds that the form 96.1% of the bagasse ash by mass; the chemical exergy is calculated to be 244.2kJ/kg as detailed in Table 11. Considering the heat lost by the bagasse ash is 0.37% of the flue gas, its thermal can be neglected. The specific exergy of the bagasse ash is therefore equal to its specific chemical exergy (244.2kJ/kg).

Table 10 - Chemical composition of residual sugarcane bagasse ash (Cordeiro et al., 2004)

Component	Weight fraction (%)	Component	Weight fraction (%)
$\mathbf{SiO_2}$	78.34	MnO	0.13
$\mathbf{Al_2O_3}$	8.55	TiO_2	0.50

$\mathbf{Fe_2O_3}$	3.61	MgO	1.65
$\mathbf{CaO}$	2.15	BaO	<0.16
$\mathbf{Na_2O}$	0.12	P_2O_5	1.07
$\mathbf{K_2O}$	3.46		

Table 11 - Chemical exergy of bagasse ash

Compound	Specific Ch. Exergy (kJ/mol)	Specific Ch. Exergy (kJ/kg)	Mass fraction (%)	Ch. Exergy per kg of bagasse (kJ/kg)
$\mathbf{SiO_2}$	2.2	36.18	78.34	28.34
$\mathbf{Al_2O_3}$	15	147.11	8.55	12.57
$\mathbf{Fe_2O_3}$	12.4	77.64	3.61	2.80
$\mathbf{CaO}$	127.3	2269.97	2.15	48.78
$\mathbf{K_2O}$	413.1	4385.35	3.46	151.73
Total			96.11	244.22 kJ/kg

6.7.7. Exergy lost due to wall losses

In normal operation, the losses from the system are in the form of wall losses and unburned fuel. In the modified scenario, complete burning is assumed; therefore the only losses considered are heat losses through the wall, which includes all forms of heat loss from the furnace. A simplifying assumption is made here by considering these losses as one heat stream. The exergy of this heat stream is given as:

$$\dot{Ex}_{wall\ losses} = \dot{Q}_{losses}(1 - \frac{T_0}{T})$$

Where T is the temperature of the heat stream and is assumed to be the average of the flue and adiabatic flame temperature.

By modelling all the mass and energy flows in terms of exergy, the exergy balance was implemented and the results are shown in Table 12.

Table 12 - Exergy flows in the baseline and modified operation of the jaggery making process

	Baseline operation			Modified operation		
Flows IN	Mass flow rate (kg/s)	Specific exergy (kJ/kg)	Exergy (kJ/s)	Mass flow rate (kg/s)	Specific Exergy (kJ/kg)	Exergy (kJ/s)
Juice	10.8×10^{-2}	3141.0	339.23	10.8×10^{-2}	3141.0	339.2
Bagasse	6×10^{-2}	13200	792.0	4×10^{-2}	13200	492.0
Air[1]	-	0	0	-	0	0
OUT flows	Mass flow rate (kg/s)	Specific exergy (kJ/kg)	Exergy (kJ/s)	Mass flow rate (kg/s)	Specific Exergy (kJ/kg)	Exergy (kJ/s)
Jaggery	2×10^{-2}	14025.0	280.5	2×10^{-2}	14025.0	280.5
Water vapour	9×10^{-2}	488.4	43.9	9×10^{-2}	488.4	43.9
Flue gas	3.4×10^{-1}	678.7[2]+445.5[3]	382.2	2.5×10^{-1}	360.8[2]+445.45[3]	201.6
Losses[4]	-	-	92.2	-	-	52.8
Ash[5]	1.5×10^{-3}	244.2	0.36	1×10^{-3}	244.22	2.4×10^{-2}

Table 13 - Performance comparison for the jaggery production

	Baseline operation	Modified operation	Percentage change
Energy efficiency	29%	40%	11%
Exergy efficiency	28.7%	39%	10.3%
Exergy destruction	332.04kJ/s or 29.6%	252.8kJ/s or 30.4%	0.8%

[1] Exergy of incoming air at the ambient temperature is zero, therefore mass flow rate is not required
[2] Thermo-mechanical exergy part of flue gas
[3] Chemical exergy of CO_2 part of flue gas
[4] Exergy due to heat losses calculated based on the quantity of heat loss from the system.
[5] Exergy due to ash heat loss is calculated based on the quantity of heat loss from the energy balance.

6.8. Results and discussion

Based on experimental measurements of the base case, the energy efficiency of the process was improved by ensuring complete combustion. This was accomplished by shifting to a controlled and lowered bagasse feed rate that also increased the batch processing time. This had an effect of lowering the operating temperature of the furnace thus reducing the flue gas temperature from 900^{o}C to 700^{o}C. It should be noted that this was the minimum possible operating temperature at which the product quality was not affected. Therefore the baseline operation was modified by reducing the furnace operating temperature to a minimum to improve the energy efficiency of the process.

The analysis and results of the jaggery process show an improvement in performance through implementing the operational modifications. The results from Table 12 and Table 13 show that the energy and exergy efficiencies increase by 11% and 10.3% respectively. The exergy destruction rate reduces by 79.24kJ/s while its percentage remains the same at about 30%. Three of the four indicators suggest an improved system whereas the percentage of exergy destroyed remains the same. Since the proportion of exergy destruction did not reduce, it merited further investigation.

6.8.1. Major causes of exergy destruction

There are two dominant exergy supplies to the system therefore two sources of exergy destruction, namely the juice and bagasse. The energy and mass transformations in these two flows are now discussed.

As the juice is heated up in pans, the sucrose $(\mathrm{C_{12}H_{22}O_{11}})$ molecules are broken down into glucose/fructose $(\mathrm{C_6H_{12}O_6})$. Sucrose being the more complex molecule has a greater specific chemical exergy, 17450kJ/kg as compared to glucose/fructose (14025kJ/kg). For the mass flow rates of the cane juice and jaggery of 0.108kg/s and 0.02kg/s respectively, there is an unavoidable exergy destruction rate of 58.7kJ/s. This exergy loss is related to the changes in the chemical structure of the sugars that flow through the process. If exergy is considered to be a measure of resource value (M. A. Rosen, 2002; Rosen, 2008; Alicia Valero et al., 2010), then the breaking down of sucrose molecules to glucose and fructose represents a theoretical loss of value. Since, this loss is exactly the same in both scenarios, the second major exergy source, bagasse flow is analysed next.

The furnace operation was analysed in detail to understand how well the combustion process uses the renewable resource (bagasse) supplied. Table 14 shows the results of an exergy balance when only the bagasse feed and the thermal flows related to combustion are considered, this allows understanding of how efficiently the bagasse is used up in the furnace.

The results from Table 15 show that the process modifications increase the energy and exergy efficiencies by 11% and 3.7% respectively. The rate of exergy destruction decreases from 403.5kJ/s to 292.2kJ/s however, as a proportion of the rate of exergy input to the furnace, its destruction actually increases by 10.32%. This increase is responsible for the exergy destruction percentage not reducing in the modified scenario. While the increase in efficiency and decrease in the absolute value of exergy destruction are beneficial for resource efficiency, the increased proportion of exergy destruction is a negative impact and is discussed in detail in the sections that follow.

Table 14 - Exergy flows for combustion in the furnace

Baseline Operation				**Modified Operation**			
Stream IN	**Value(kJ/s)**	**Stream OUT**	**Value(kJ/s)**	**Stream IN**	**Value(kJ/s)**	**Stream OUT**	**Value(kJ/s)**
Bagasse	792 (100%)	Jaggery heat content	0.64 (0.1%)	Bagasse	492 (100%)	Jaggery heat content	0.64 (0.13%)
Air	0	Vapour	43.9 (5.4%)	Air	0	Vapour	43.9 (8.9%)
		Flue	230.7 (29%)			Flue	90.2 (18%)
		Losses	92.2 (11.6%)			Losses	52.8 (10.7%)
		Destruction	424.5 (53.6%)			Destruction	314.5 (63.9%)

Table 15 - Performance comparison for combustion in the furnace

Performance Comparison			
	Normal Operation	Altered Operation	Percentage change
Energy efficiency	29%	40%	11%
Exergy efficiency	5.62%	9.35%	3.73%
Exergy Destruction	53.59%	63.91%	10.32%

6.9. Implications for industrial symbiosis

Summarising the results from the previous section, the process modifications resulted in a reduced absolute amount of exergy loss, decreased proportion of flue losses and an increased proportion of exergy destruction. These results have implications for potential industrial symbiosis (IS), and are now discussed.

While the local operational modifications make the jaggery process more efficient, there were two negative impacts on the whole system resource consumption.

- Increased proportion of exergy destruction
- Decreased available exergy to a possible secondary process

All exergy losses from the jaggery furnace result in resource consumption, however flows such as flue gas exergy may be recoverable if an appropriate opportunity is available. On the hand, exergy destruction represents losses due to thermodynamic irreversibilities that can never be recovered, and therefore should be minimized. Additionally, the proportion of exergy availability to a secondary process was reduced and is reflected in the reduced exergy value of the flue gas leaving the jaggery furnace. In an IS system, the goal is to reduce the resource consumption of a larger system such as an industrial park through integrations between individual systems and processes. To this effect, the positive impacts of operational modifications should outweigh its negatives in the integrated system.

A possible symbiosis is explored in Figure 34, where a hypothetical secondary process (called X), which is fired by non-renewable fuel, is to be integrated with the jaggery process in such a way that its fuel use can be reduced through the input of waste heat from flue gases of the jaggery process. Recall that in terms of the percentage of supplied exergy, the flue gas exergy reduced from 29% (230.7kJ/s) in the baseline scenario to 18% (90.2kJ/s) in the modified scenario, see Figure 34.

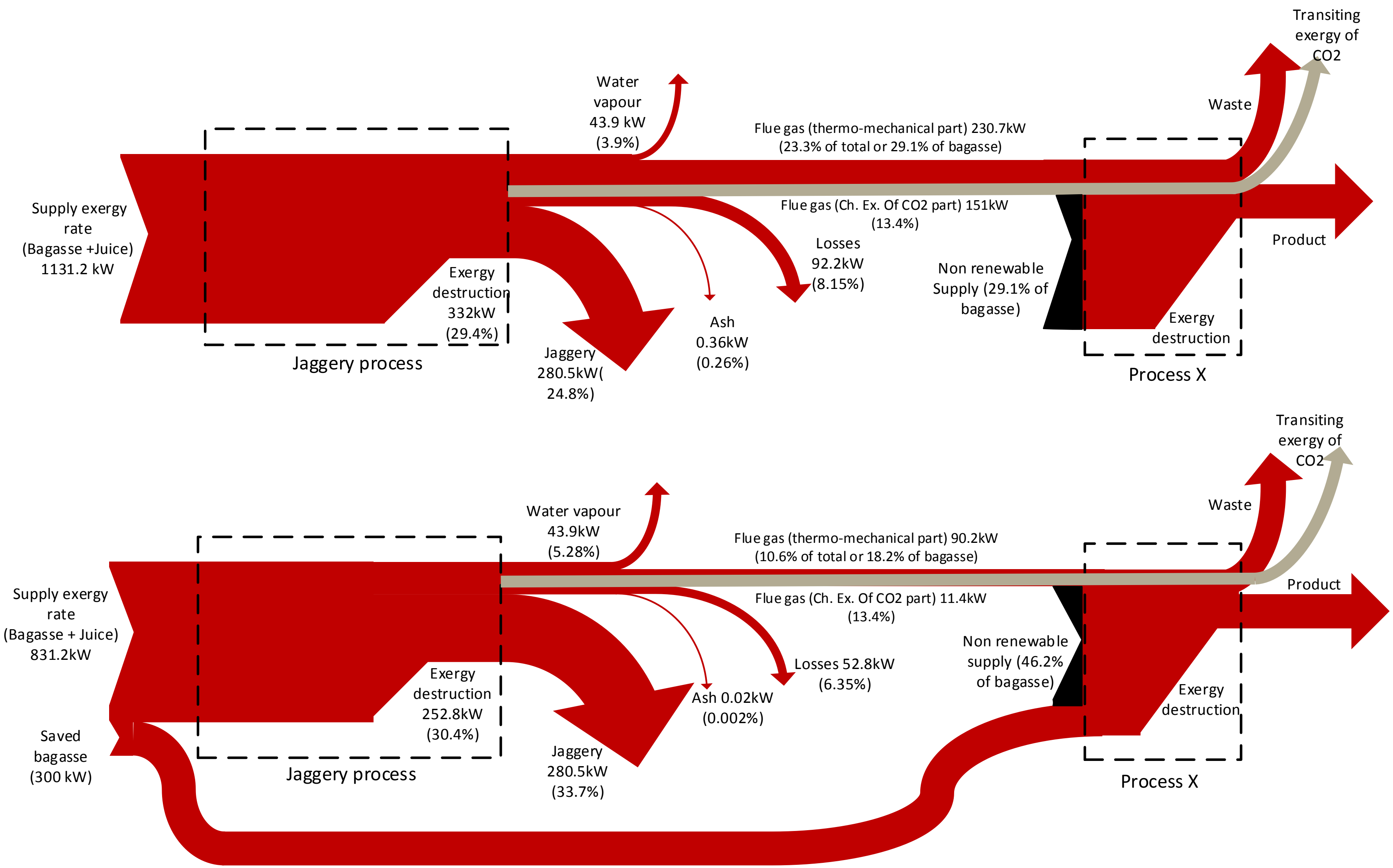

Figure 34 - Integration of the jaggery process with a secondary process X for the baseline operation (above) and modified operation (below)

This means that in the integrated system, the secondary process has less renewable exergy available from the flue gas. On the other hand, the modifications also result in saved bagasse that could then be used in the secondary process, resulting in reduced non-renewable exergy supplied to the system. Consequently, in the integrated system, the modifications also lead to performance improvements compared to the baseline scenario. A reduction in non-renewable supply of 46.2% of bagasse would be observed in the modified operation as compared to 29.1% in the baseline. Therefore, the modified scenario would use 17.1% less exergy compared to the baseline, even with an increased proportion of exergy destruction within the furnace. For this example, the negative impact of increasing the proportion of exergy destruction in the furnace is outweighed by the positive impact of increased efficiency of the hypothetical industrial symbiosis.

The Grassmann diagrams in Figure 34 allow a comparison of chemical and thermal exergy flows. The produced jaggery represents a substantial flow where thermal exergy content is negligible compared to its chemical exergy. Similarly the chemical exergy of CO_2 is also significant and leaves the system as transiting exergy. The exergy of these CO_2 emissions could be understood in terms of its impact on the natural environment. Consequently, researchers have measured environmental impact through exergy based indicators (Ao et al., 2008).

In addition to modelling all flows through a jaggery process in terms of exergy, this analysis showed how exergy destruction varied with the modifications and in what way it affected the integrated system. It is noteworthy here, that the modified option still operates with almost 64% exergy destruction. Perhaps, a third option that operates at higher furnace temperatures might reduce this loss as well, and is the subject of discussion in the following section.

6.10. Symbiosis with increased furnace temperature

We now consider a third possible option in which where the furnace is operated at a higher temperature than baseline. Since this study was based on pre-collected data, an actual experimental option was not performed; in fact the option is hypothesized based on established literature. Hottel (1988) has shown that for a furnace in general, as the operating temperature of furnaces increases, the difference between the flue gas and the furnace operating temperature reduces. This effectively reduces the exergy destruction, which is simply the difference between the exergy that flows into and out of the furnace. Recall that in the Jaggery case study, the proposed modifications had the effect of increasing exergy destruction compared to the baseline. This supports Hottel's generalization and suggests that increasing the operating temperature of the jaggery furnace (instead of decreasing it) would reduce exergy destruction in this case study as well. Figure 35 depicts this concept to aid the reader in understanding this point.

In the context of industrial symbiosis, if the jaggery furnace operates at an increased temperature, a greater proportion of the flue gas exergy would be available to the secondary process. Since exergy destruction is the largest cause of exergy loss in the furnace baseline operation (53.6%), increasing the furnace temperature would target the reduction of this loss. For this option to be more viable than the modified scenario, the combined exergy savings in the exergy destruction and the increased flue gas exergy should be greater than 17.1%. However, an experimental or simulation study would be required to see if this is actually possible. Examples of furnace simulations are abundant in literature (Auchet et al., 2008; Tucker and Ward, 2012); however most approaches are too detailed to be suitable for decision making in the current context. A simplified simulation methodology applicable to a furnace in general that can accurately predict the effect of the furnace outputs with changing operating conditions might be of some benefit to resource optimization in integrated systems with furnaces involved.

Nonetheless, this does not detract from the goal of this study, which was to demonstrate how the approach could be applied in practice. It was shown that exergy destruction and non-renewable exergy supply are useful indicators for investigating and assessing the sustainability of integrated systems.

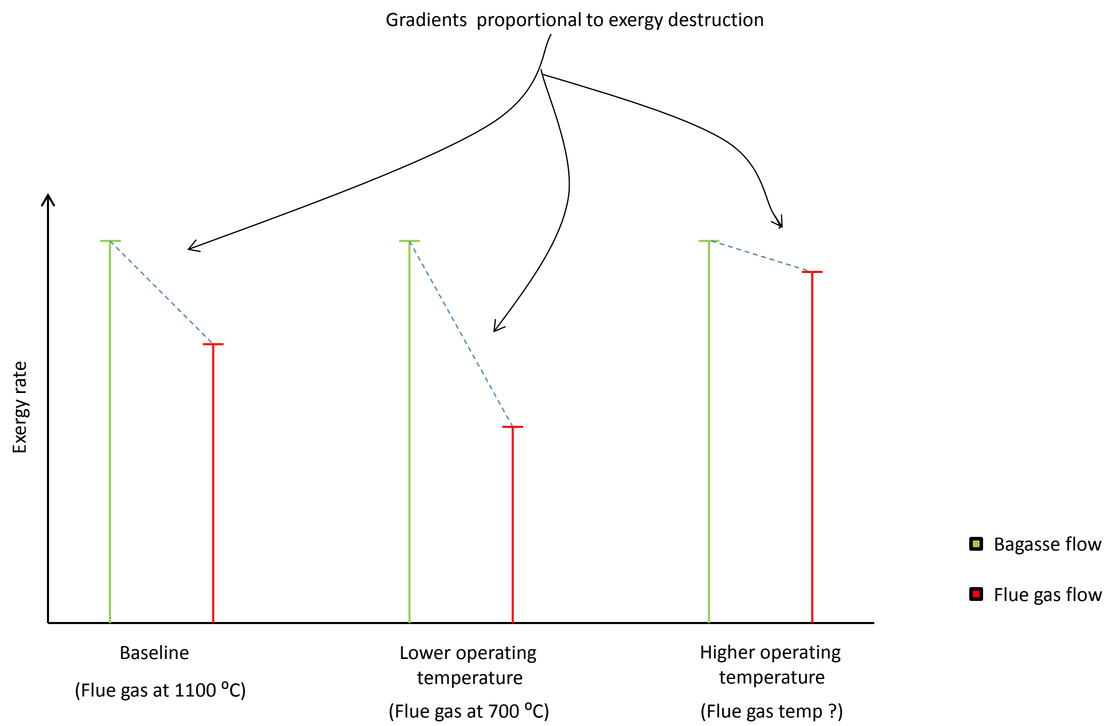

Figure 35 - Variation of exergy destruction with flue gas temperature

6.11. Summary and concluding comments:

This chapter presented the first use of exergy analysis to quantify natural resource consumption of a jaggery process. The most significant loss of value was due to exergy destruction in the combustion process (a furnace fired by renewable exergy). Based on experimental data from a previous study, the baseline was compared with the modified scenario. For the individual process, exergy efficiency for the baseline and modified scenarios were 28.7% and 39% respectively. The exergy destruction however remained steady at about 30% of the total exergy supplied to the process. A deeper investigation revealed that increasing efficiency of the furnace through a reduction in its operating temperature had an associated negative impact of an increased proportion of exergy destruction. This insight has significance for decision making in industrial symbiosis. By considering a hypothetical symbiotic process X, the whole integrated system resource use was analysed. The secondary process is considered that uses the exergy output from the jaggery process to displace some of its supply of non-renewable exergy. This would reduce the overall non-renewable exergy supplied to the whole system by an additional 17.1% compared to the baseline. The exergy concept was therefore used to quantify the resource efficiency impact of symbiosis. A third scenario could be explored in which resource efficiency might be improved by increasing the operating temperature of the furnace. A higher operating temperature would target the largest exergy loss in the process, which is exergy destruction. Note that while this case study was essentially of a thermal system and waste heat reuse, this chapter illustrates how a variation of mass and energy flows with varying quality levels can be modelled in terms of exergy. Therefore in principle, through this approach, resource accounting could be performed in IS systems that may employ a range of manufacturing system designs.

Chapter 7

Case study 3 - Exergy modelling of water flows in manufacturing

7.1. Introduction:

When considering natural resource consumption in manufacturing, accounting for clean water consumption is increasingly important. Therefore, a holistic methodology for resource accounting in factories must be able to account for water efficiency as well.

This chapter presents a case study of a food processing facility where its water efficiency is as important as its energy efficiency. The conceptual approach presented earlier is used to account for the resource consumption in the facility. The approach requires modelling of all flows through the system in terms of exergy and this is accomplished for the energy and water flows in the factory. The resource consumption of the factory is quantified and compared with an improved scenario where exergy is reused. This is done by considering a hypothetical wastewater treatment process. To the author's knowledge, this study presents the first instance where the methodology for modelling wastewater as exergy is carried out in the context of a manufacturing system. Finally, the findings and conclusions are listed along with the strengths and limitations of applying the conceptual approach in the context of this case.

7.2. Background to the factory and its resource use:

The food company is a manufacturer of a variety of ready meals in the UK market. Its production output was 25,628 tons of meals for the year 2013 (Fuentes, 2014). As a result the food factory works 24/7 and has a significant cost associated with its resource use. The production equipment is broadly comprised of ovens and pans for cooking the raw material. Afterwards, the products are cooled in chilled rooms and packed for transportation. Cleaning the production facility is of utmost importance due to the nature of the product because of which extensive washing and cleaning processes exist. Excluding the raw material supply, Table 16 presents the total resources supplied to the facility in terms of energy and clean water usage.

Table 16 – Weekly average resource consumption of food factory

Year	Gas(kWh)	Electricity (kWh)	Water(m^3)
2011	913,324		3302
2012	679,290	224,898	3335
2013	728,257	224,351	3542
2014[6]	737,920	204,434	3510

The figures in Table 16 show that water use is a significant part of the overall resource consumption and it should be considered at par with gas and electricity. However it should be noted that the resources compared in Table 16 use two different units, kWh and m^3. A better comparison of the resource use can perhaps be made if they are expressed in common units. This case study describes how the conceptual model presented in chapter 4 can be used to assess all flows through the factory on equal basis objectively. The following section describes the research methodology adopted in order to assess the resource use of the food production facility.

7.3. Methodology:

The main goal of this study is to demonstrate the application of the conceptual approach to a case of water efficiency. To this effect, there are two sub-objectives which are as follows,

i. To model the energy and water flows through the factory in terms of exergy.
ii. To compare the baseline with a hypothetical improved scenario in order to demonstrate the ability of the approach to compare different technology options.

It should be noted here that conducting a highly accurate feasibility for water reuse is not the goal of this study. Rather, the comparison of the baseline with the hypothetical scenario should indicate how the conceptual approach might be applied in practice. Since the aim is to compare exergy reuse options, Figure 36 shows the part of the conceptual approach to be focused upon outlined in red.

[6] Weekly average based on actual data collected from Jan-March

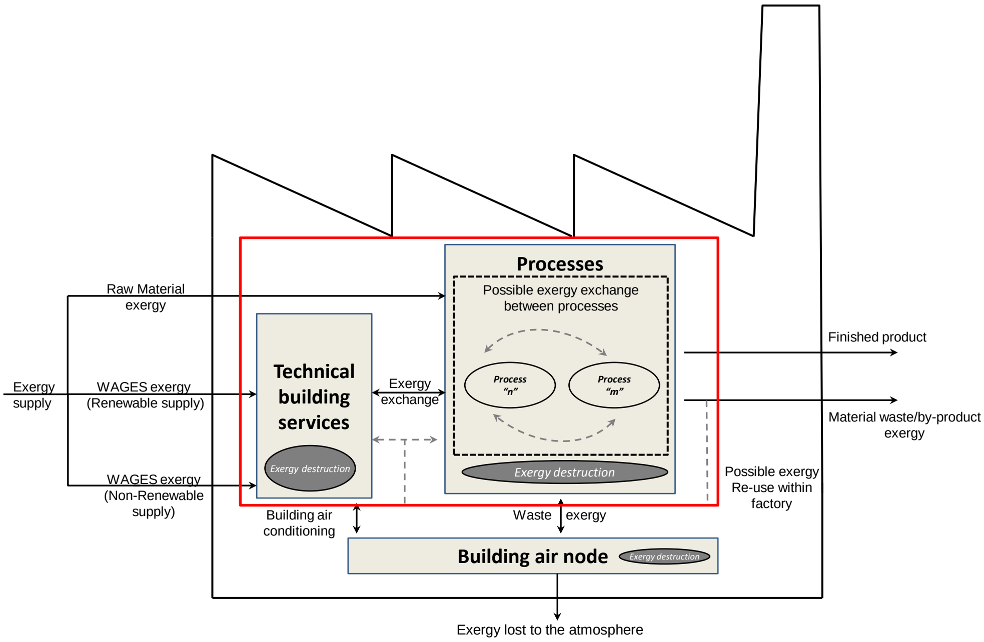

Figure 36 - The conceptual approach with the portion in focus for this case study outlined

Data for this study were collected through factory visits. On the supply side, the overall resource use data were provided by the factory management. For the effluent water, a heat meter was used to measure its flow rate and temperature. The sample of the effluent water was taken from an open flow channel just before drainage to the environment. The chemical composition of the sample required for the chemical exergy calculation was acquired through a water quality testing lab facility Staffordshire water services (2014). The following section presents a summary of the literature in which exergy analysis has been used to model water flows.

7.4. Application of exergy analysis for wastewater treatment:

As the presence of impurities in wastewater means a variation from the exergy reference environment, effluent water at varying levels of impurity can be translated into values of exergy. Additionally, all flows in a water treatment process can be expressed in common physical units of exergy.

In such a case, the sustainability of a water treatment process can be expressed by a single indicator, its exergy efficiency (Balkema et al., 2002). Since usual environmental reporting has a long list of different and incompatible indicators, the use of exergy to quantify the various impacts in common units is certainly beneficial. Its drawback however, lies in its context dependant ability to quantify environmental impact. For instance Ayres et al. (1998) claim the embodied exergy in a waste stream is not a reliable measure of its toxicity. Similar conclusions have been reached by other researchers such as Ao et al. (2008) and Gaudreau et al. (2009). Therefore calculations of exergy alone are insufficient to quantify waste impacts. However, this does not detract from the fact that it is certainly a more realistic indicator than either mass or energy for measuring environmental impact. This is why researchers such as Mora and Oliveira (2006) used exergy to evaluate the environmental impact of two wastewater treatments. In the article, Mora used two indicators, exergy efficiency and the total pollution rate, to measure the environmental impact of the wastewater treatment process. The by-products of this treatment are useful outputs, methane gas and sludge cake (used as a fertilizer) that offset the exergy requirements of the process. Seckin and Bayulken (2013) calculated the exergy required to treat municipal wastewater (exergy of remediation) for the Turkish household sector. The treatment process used was anaerobic digestion as it is suitable for treating water effluent with high organic content. However the article was based on an extended exergy analysis which translates monetary costs related to capital and labour to its exergy equivalents. Therefore, the analysis by Seckin and Bayulken (2013) cannot be considered a strictly thermodynamic analysis. One of the earliest examples of using the exergy concept to quantify resource consumption in wastewater treatment is the article by Hellström (1997). The study showed that energy analysis has the limitation of overestimating the value of the waste heat in the effluent water. On the other hand, Hellström found that exergy analysis underestimated the decrease in phosphorous resources as well as not being able to measure toxicity. He concluded that exergy analysis is an imperfect but greatly improved tool compared to energy analysis for the purposes of quantifying physical resource consumption in water treatment, which is the view adopted by the author as well.

The review of literature shows that exergy has thus far only been used to model water flows for natural water bodies and urban wastewater scenarios (Chen and Ji, 2007). To the author’s knowledge, the exergy assessment of water effluent from a manufacturing facility in the UK has not been conducted before. The method to calculate the exergy for a water sample is now described in detail as it is the core methodology of this chapter.

7.5. Selection of the reference environment (RE):

Since exergy is a property of both the system and the environment, the choice of the RE will directly influence the results obtained. Since this chapter presents the approach to modelling water flows in a factory, it is imperative to describe the available options for the water present in the reference environment (RE). The RE water has to represent the ‘dead state’, so its makeup should approximate the composition of water that represents zero potential to cause change and is found most abundantly on earth. Martínez and Uche (2010) briefly describe the most reasonable choices for the water in the RE and their strengths and limitations are discussed as follows.

7.5.1. Water with high concentrations of impurities:

A high concentration of impurities such as high levels of organic matter nitrates and phosphates represents highly polluted water. This choice of RE water could be useful for assessing environmental impact, but its main limitation lies in the fact that it is not representative of the water present in the natural environment.

7.5.2. Spring water:

Spring water contains pure water with useful minerals and seems a potentially suitable choice if charting the degradation of natural rivers is required. However, the composition of spring water is different in each river basin thus making a global assessment impossible. Additionally, spring water is not the most abundant form of water on earth and is not representative of the water in the natural environment.

7.5.3. Pure water:

A sample of pure water would only contain H_2O molecules. Since no impurities would be present in the RE water, only the formation exergy calculation needs to be done. This option will therefore simplify the chemical exergy calculation method and may be a suitable choice, however it contradicts reality as the majority of water present in the reservoirs of planet earth is in the sea and is not pure water.

7.5.4. Seawater with organic matter:

As seawater constitutes the bulk of the water present on earth, a certain composition of it can be a choice representative of reality. Impurities in water can be classified as organic and inorganic, and therefore a particular concentration of these can be assigned to the RE water. Since both organic and inorganic content is assumed to be present in this choice for RE water, only the concentration exergy needs to be calculated.

7.5.5. Seawater without organic matter:

The seawater on planet earth has a high concentration of salts, and is considered to have negligible organic content. If the RE water is selected as seawater without organic matter, then it is a choice that is similar to the composition of actual sea water. Waters on the surface that are at variation from this state (e.g. natural springs and rivers) also eventually end up in the sea and lose their chemical exergy due to mixing with the dead state (seawater). Since inorganic matter is considered present in the RE, their concentration exergy needs to be calculated whereas for the organic content, the chemical formation exergy is required.

7.5.6. RE water selection:

From the choices described above, seawater without organic content has been the one selected for this chapter and is also the choice of prominent researchers such as Szargut et al. (2005b) and Valero et al. (2009b). The first three choices described above are either not representative of the reality or do not represent the thermodynamic 'dead sate', and are therefore unsuitable. The reason for selecting seawater without organic content as compared to seawater with organic content is as follows.

For the case when organic matter is considered part of RE seawater, the concentration exergy formula involves a natural logarithmic function that underestimates the work potential of the organic matter in a water sample. Figure 37 illustrates this limitation by plotting the increase of exergy in response to increasing total organic content (TOC). The figure shows that when organic matter is considered part of the RE water; there is an insufficient increase in the specific exergy that does not correspond to the value of the increased organic content, thus underestimates the value of the organic content. This limitation is not observed for the choice of RE seawater without organic content and is therefore a more suitable choice. Based on this selection of RE water, the methodology for calculating the exergy of the supply and effluent water is now described.

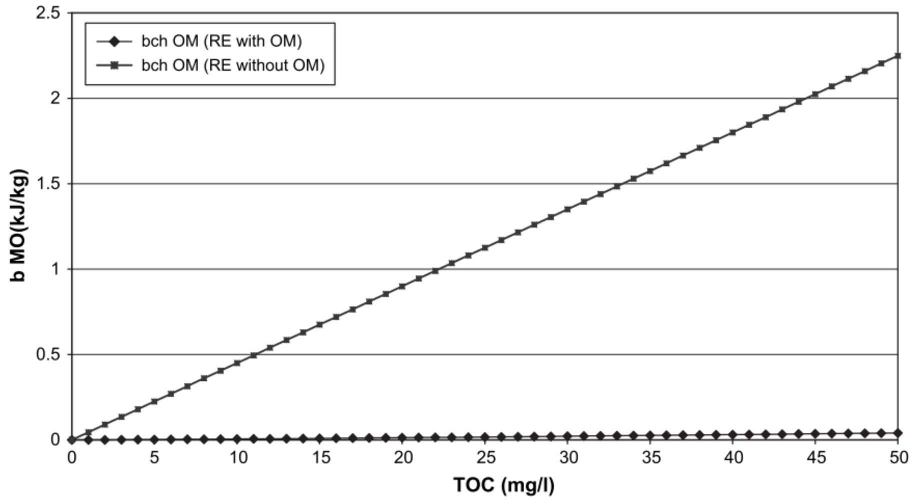

Figure 37 - Effect on specific exergy due to consideration of total organic content in the RE water (Martínez and Uche, 2010)

7.6. Calculating exergy of water (method):

The total exergy of a mass flow in general is comprised of five parts, (1) thermo-mechanical(2) kinetic (3)potential (4) chemical formation and (5) chemical concentration exergy (Gundersen, 2009):

$$ex_{total} = ex_{thermo-mechical} + ex_{formation} + ex_{concentration} + ex_{kinetic} + ex_{potential}$$

The calculation of each term in the above equation in context of the water sample from the factory is now described.

7.6.1. Thermo-mechanical exergy:

The thermo-mechanical exergy component is due to the temperature and pressure of the water flow. The thermal exergy component is calculated using the difference in temperature of the water sample and the reference environment. In the current study, the temperature of the water effluent was recorded using ultrasonic heat flow measurement equipment. The mechanical exergy component is calculated using the specific volume and the pressure differential that exists between the water sample and the RE. This exergy component is calculated using equation (1) as follows,

$$ex_{thermo-mechical} = c_p \left[T - T_0 - T_0 \, ln\left(\frac{T}{T_0}\right)\right] + v(p - p_0) \qquad (7.1)$$

From the equation it can be seen that since the effluent water is at atmospheric pressure, its mechanical component is zero. The average temperature of the effluent water recorded was T

(29.8°C). The RE temperature $T_0$and the specific heat capacity of water c_p used are 298.15K and 4.2kJ/kgK respectively.

7.6.2. Kinetic and potential exergy:

This component is calculated exactly similar to kinetic and potential energy. The kinetic exergy is calculated using the absolute velocity measurement at the point where the water sample is taken. Potential exergy, similar to potential energy depends on the height form a reference. Both these exergy components can be calculated using equation (2). However, owing to the low velocity of the effluent water from the factory and height of the effluent flow, its value will be negligible as compared to the chemical exergy component (Antonio Valero et al., 2012).

$$ex_{kinetic} + ex_{potential} = \frac{1}{2}\left(\vec{V}^2 - \vec{V}_0^2\right) + g(h - h_0) \qquad (7.2)$$

7.6.3. Chemical exergy:

For modelling water flows, chemical exergy is the major component that needs to be calculated and depends on the composition as well as the concentration of a substance dissolved in a mass sample. In the case of the food process effluent, it would be the dissolved impurities in the water sample. The chemical exergy is composed of two parts, the concentration exergy and the chemical formation exergy. Concentration exergy is calculated for the substances in the water sample that are already present in the RE water. The formation exergy is calculated for those substances that are not present in the RE water. Additionally, the substance dissolved in the water can be categorized into organics and inorganics (Armando et al., 2003). As the selected water in the RE is seawater without organics, formation exergy is calculated for the organic content whereas concentration exergy is calculated for the inorganic substances in the water sample.

7.6.4. Chemical formation exergy (organic portion):

Since formation exergy is calculated for those substances that are not present in the RE, their synthesis through its appropriate chemical reaction needs to be considered. It is the minimum energy required to form the chemical substance using the elements present in the reference environment. It is calculated using the Gibbs free energy, a property of a thermodynamic system that is defined as follows,

$$G = H - TS \qquad (7.3)$$

Where *G, T* and *S* are the Gibbs free energy, absolute temperature and entropy respectively. As a chemical reaction proceeds, the change in the Gibbs free energy, ΔG can be thought of as the maximum work obtainable from the reaction. It can also be thought of as the work output in an isothermal expansion. It can be calculated using equation (3) with the Gibbs free energy at standard conditions, ΔG^0 which is tabulated in easily available thermodynamic property tables such as (Lide, 2007). For a general reversible chemical reaction,

$$xA + yB \leftrightarrow zC \qquad (7.4)$$

Where *C* is the product, and *A, B* are the reactants. The alphabets *x, y* and *z* represent the moles of its corresponding substance based on the stoichiometric balanced chemical reaction. It should be noted that in weak solutions such as the water sample considered in this study, the activity is equal to the molarity (mol/L). Since ΔG represents the maximum work obtainable from the chemical reaction, it is by definition the chemical formation exergy (Tai et al., 1986) and is calculated by equation (5) as follows.

$$ex_{formation} = \Delta G = \Delta G^0 + RT\ln[\frac{a^z}{b^x c^y}] \qquad (7.5)$$

Where *R* is the universal gas constant (8.314 J/kgK), *T* is the reference environment temperature (298.15K), *a, b* and *c* represent the activity of each substance. The standard chemical exergies of elements and common compounds have been tabulated by Szargut et al. (2005a) and can also be found in online databases such as the (CIRCE, 2008). The exergy of all the impurities present in the effluent water needs to calculated and summed up according to their relative proportions present in a kilogram of the water sample (Zaleta-Aguilar et al., 1998).

Since the water in the RE is devoid of organic matter, the formation exergy of the organic content needs to be calculated. For this purpose, a representative molecule needs to be taken to approximate the organic content. The actual make of the organic content will have a large variation in chemical composition, but the assumption of a 'mean organic substance' molecule needs to be made in order to calculate the chemical formation exergy. Different researchers have used different 'mean organic substances', for example (Armando et al., 2003) has used the fat molecule $C_{39}H_{80}O_3$. The 'chemical oxygen demand' or COD test measures the oxygen demand of a water sample in $O_2/litre$ and is used to quantify the amount of the organic substance through the balanced chemical reaction as follows.

$$C_{39}H_{80}O_3 + 57.5O_2 \Leftrightarrow 39CO_2 + 40H_2O \qquad (7.6)$$

This chemical reaction represents the oxidation of the organic molecule to form the products of the reaction. The exergy content of the fat molecule can be calculated using the earlier described method for the standard chemical exergy of formation. The standard chemical exergy of this substance along with 137 other organic compounds have been listed by Tai et al. (1986). Other researchers have also used CH_2O as a typical organic molecule; Martínez and Uche (2010) compare the results obtained by using the two different molecules. Considering a variety of organic compounds, Tai et al. (1986)found a correlation between the standard specific chemical exergy of 138 organic substances in a water sample to the COD value which is given by equation (7) as follows.

$$ex(J/L) = 13.6 \times COD(mg/L) \qquad (7.7)$$

Since the organic content represents a significant source of exergy in the water sample, the exergy due to organic matter is calculated using all the three approach and the results are later compared.

7.6.5. Chemical concentration exergy (inorganic part):

For substances that are already present in the RE water, their difference in the concentration in the water sample and in the RE represents a theoretical work potential and is termed as the concentration exergy. Concentrations of various chemical substances that are commonly present in the RE along with the standard chemical exergy values were calculated by Szargut et al. (2005b) which have been updated by Rivero and Garfias (2006) and are used in this case study. The exergy content due to the inorganics has to be calculated from the concentration of those substances present in the water sample and need to be directly measured (B. Chen et al., 2009). The chemical concentration exergy is calculated through equation (8) as follows,

$$ex_{concentration} = RT_0 \sum_k x_k \ln\left(\frac{C_k}{C_0}\right) \qquad (7.8)$$

Where R is the universal gas constant (8.314 *J/mol.K*) and T_0 is the reference environment temperature (288.15K). Also, *x* is the molar fraction and *C* is the concentration. The subscript *k* is the number of the substances within the mass with their respective concentrations and finally, the subscript *o* indicates that the property is at the reference environment condition.

7.6.6. The total exergy:

The total exergy for an incompressible substance can be calculated through equation (9) as,

$$ex_{total} =$$
$$c_p \left[T - T_0 - T_0 \ln\left(\frac{T}{T_0}\right)\right] + v(p - p_0) + \sum_i y_i \left[\Delta G^0 + \sum n_j ex_{chem,j}\right] + RT_0 \sum_k x_k \ln\left(\frac{C_k}{C_0}\right) +$$
$$\frac{1}{2}(V^2 - V_0^2) + g(h - h_0) \qquad (7.9)$$

where the formation exergy is expressed slightly differently in order to make its calculation easier. n_j is the number of moles of the element in the compound and is multiplied with its standard chemical exergy in the RE, and y_i is the molar fraction of the element in the compound. In the case of the water effluent from the food manufacturing facility, it will be shown later that the major contribution to the exergy content is due to its chemical composition. In such a case, the total exergy equation simplifies to:

$$ex_{total} = \sum_i y_i \left[\Delta G^0 + \sum n_j ex_{chem,j}\right] + RT_0 \sum_k x_k \ln\left(\frac{C_k}{C_0}\right) \qquad (7.10)$$

7.7. Exergy of water flow (results):

7.7.1. Exergy of supply water:

The supply water is assumed to be pure water owing to the negligible quantities of impurities in it (STW 2015). It is therefore composed of only the H_2O molecule that has a specific chemical exergy of 41.67 kJ/L (CIRCE, 2008). The water consumption of the food processing plant in 2014 was 5.8 kg/s (Table 16). This amounts to a specific exergy due to supply water of 241.7kW or 40,605kWh/week.

7.7.2. Exergy of effluent water:

The effluent water flow was monitored using an ultrasonic flow meter for a week in 2014. The average mass flow rate of 4.55kg/s was recorded at a temperature of 28.9^{o}C. The chemical exergy of the effluent water sample was calculated using the water quality data acquired, and is presented in Table 17. The results show that the inorganic component is significantly smaller than the organic part. All three methods to calculate the exergy due to organic component were used, and it can be seen that there is significant variation in the results. For the purposes of this case study, the value of 52.6kJ/kg was selected that was calculated using method 3. This choice is based on the fact that the selection of the representative organic molecule is rather subjective. Furthermore, the relation obtained by Tai et al. (1986) in method 3 has been obtained for a large number of organic compounds which might be the case in the effluent water. Additionally, method 3 offers a simple calculation method and reduces the complexity in exergy calculation procedure and therefore increases its practicality.

Table 17 - Chemical test results and specific exergy calculation of the food process effluent sample

<table>
<tr><th colspan="7">Inorganic matter</th></tr>
<tr><td>Substance</td><td>Test result</td><td>Molar mass</td><td>Moles of substance in sample</td><td>Mole fraction</td><td>molarity in RE</td><td>Exergy</td></tr>
<tr><td></td><td>(mg/kg)</td><td>(g/mol)</td><td>(mol/kg)</td><td></td><td>(mol/kg)</td><td>(kJ/kg)</td></tr>
<tr><td>Chloride (Cl)</td><td>330</td><td>3.55</td><td>9.31E-03</td><td>1.39E-04</td><td>5.66E-01</td><td>-1.37E-03</td></tr>
<tr><td>Sulphate(SO4)</td><td>1.5</td><td>9.61</td><td>1.56E-05</td><td>2.34E-07</td><td>1.17E-02</td><td>-3.91E-06</td></tr>
<tr><td>Calcium(Ca)</td><td>68</td><td>4.01</td><td>1.70E-03</td><td>2.54E-05</td><td>9.60E-03</td><td>-1.06E-04</td></tr>
<tr><td>Sodium(Na)</td><td>340</td><td>2.30</td><td>1.48E-02</td><td>2.21E-04</td><td>4.74E-01</td><td>7.85E-01</td></tr>
<tr><td>Magnesium(Mg)</td><td>16</td><td>2.43</td><td>6.58E-04</td><td>9.85E-06</td><td>4.96E-02</td><td>2.87E-02</td></tr>
<tr><td>Potassium(K)</td><td>82</td><td>3.91</td><td>2.10E-03</td><td>3.14E-08</td><td>1.04E-02</td><td>6.58E-01</td></tr>
<tr><th colspan="7">Organic matter</th></tr>
<tr><td>COD</td><td colspan="6">3870 (O2/L)</td></tr>
<tr><td></td><td></td><td colspan="3">Specific exergy</td><td colspan="2">Exergy</td></tr>
<tr><td></td><td></td><td colspan="3">(kJ/mg)</td><td colspan="2">(kJ/kg)</td></tr>
<tr><td>Method 1</td><td>CH_2O</td><td colspan="3">1.73E-02</td><td colspan="2">66.8</td></tr>
<tr><td>Method 2</td><td>$C_{39}H_{80}O_3$</td><td colspan="3">4.22E-02</td><td colspan="2">54.4</td></tr>
<tr><td>Method 3</td><td>e = 13.6 x COD</td><td colspan="3">N/A</td><td colspan="2">52.6</td></tr>
</table>

Another issue that is highlighted by Table 17 is the negative values of exergy for the inorganic compounds. Since exergy represents the variation from a reference state, the negative values are meaningless. This issue with the exergy concept has been highlighted in literature before, an example being an article by Gaudreau et al. (2009), and has yet again come the fore in this case study. To counter this issue, the absolute values for the inorganic matter exergy are taken; the total specific exergy of the effluent water then becomes 54.75 kJ/kg.

In order to interpret the magnitude of exergy that the food process effluent water has, its specific exergy is compared with five other water bodies in the world that have the largest specific exergies. Figure 38 depicts this comparison which puts the exergy content of the food process effluent in perspective. It has a higher specific exergy than the Dead Sea and is 12.1 times greater than Spanish urban wastewater.

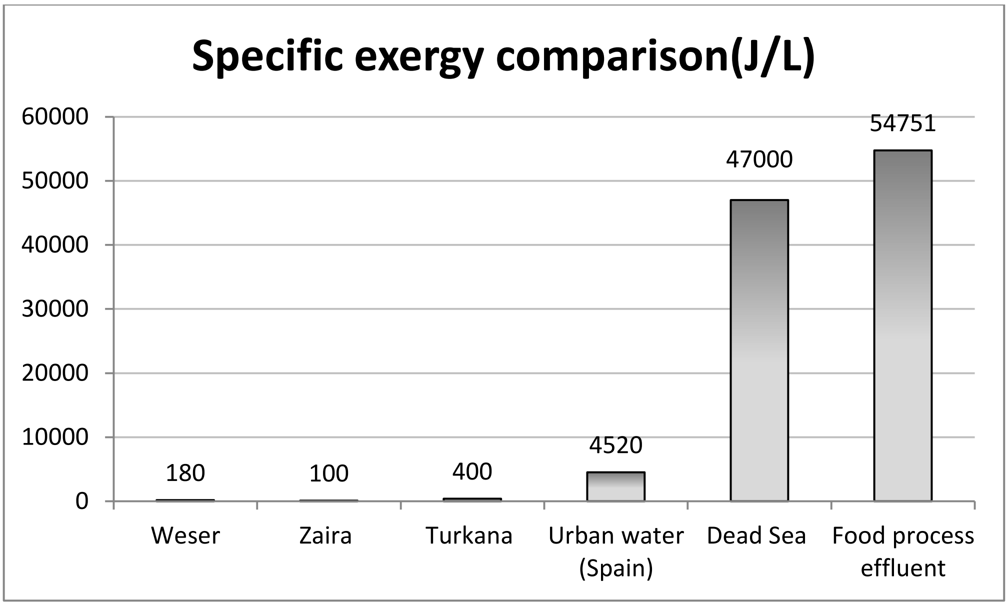

Figure 38 - comparison of the specific exergy of the food process effluent sample with other water bodies of the world (after Chen (2007))

The large value of exergy for the food process effluent suggests that it is at a significant variance from the reference environment. It should be noted here that while the specific exergy values of the Dead Sea and food process effluent are comparable, they are different in nature. The source of the high exergy content of the Dead Sea water is inorganic matter whereas for the food process effluent, it's organic matter. The organic matter is assumed to be biodegradable through an oxidation reaction and may not be considered harmful to the environment. However it does possess a significant amount of exergy and represents a good opportunity for reuse. Exergy modelling of the water flows highlights the potential of the effluent which could not have been identified using a 1^{st} law based approach.

For the average weekly mass flow rate of 4.55kg/s, the chemical exergy rate of the effluent amounts to 248.9kW or 41,815kWh/week. For the temperature of 28.9^{o}C, the specific thermal exergy content amounts to 0.073kW or 12.36kWh/week. It is noteworthy here that the thermal exergy content is only 0.03% of the chemical exergy content. It is therefore reasonable to neglect the thermal exergy component in the further analysis. The chemical exergy represents significant reuse potential and therefore the hypothetical wastewater treatment option is described next.

7.8. Water treatment:

The exergy due to organic content could be potentially be recovered through a suitable water treatment process. A common process used for recovering energy from the organic content is the anaerobic digestion process. This is a biochemical process where microorganisms in settling tanks digest and convert the organic matter in waste water to natural gas (CH_4) and residue. The residue can be used as a substitute for fertilizer and along with the natural gas produced are valuable output resulting from the treatment of water. Figure 39 shows a typical waste water treatment plant that employs the anaerobic digestion process (Mora and Oliveira, 2006). The processes in the treatment plant can be classified as (i) filtration (ii) digestion and (iii) chemical treatment. The inputs to the process are electricity, wastewater and chemicals.

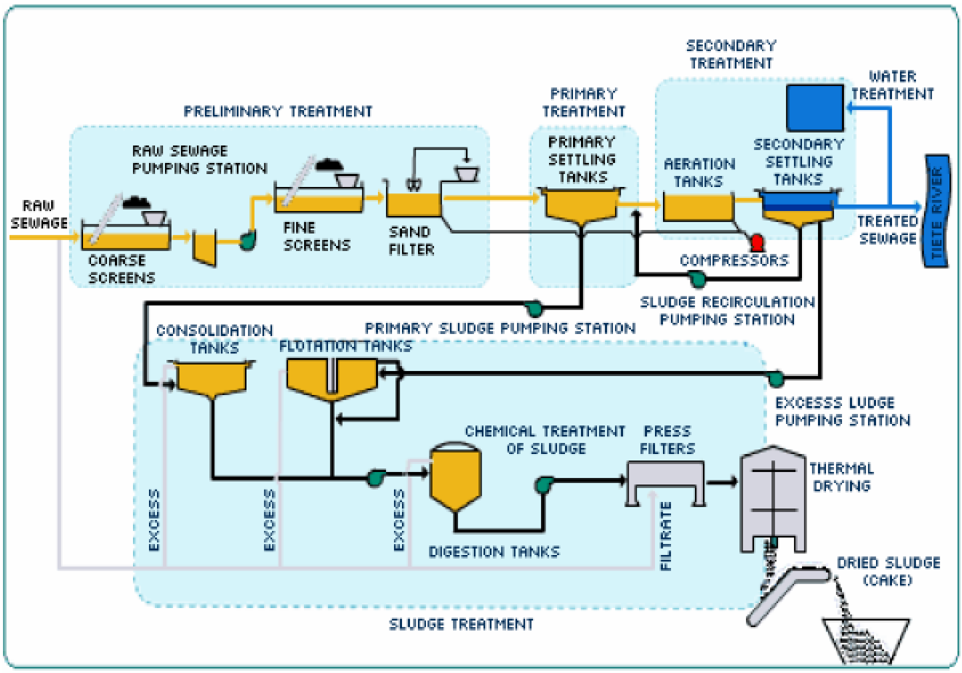

Figure 39 - A typical wastewater treatment plant that employs anaerobic digestion (Mora and Oliveira, 2006)

The organic content removal through anaerobic digestion process usually ranges between 70-80%. A study conducted by McCarty et al. (2011) investigated if wastewater could actually become net energy producers. McCarty cites low temperature and low organic content as the main barriers to direct anaerobic treatment of wastewater systems. The article considers a hypothetical wastewater treatment system that to estimate net energy recovery, see Figure 40.

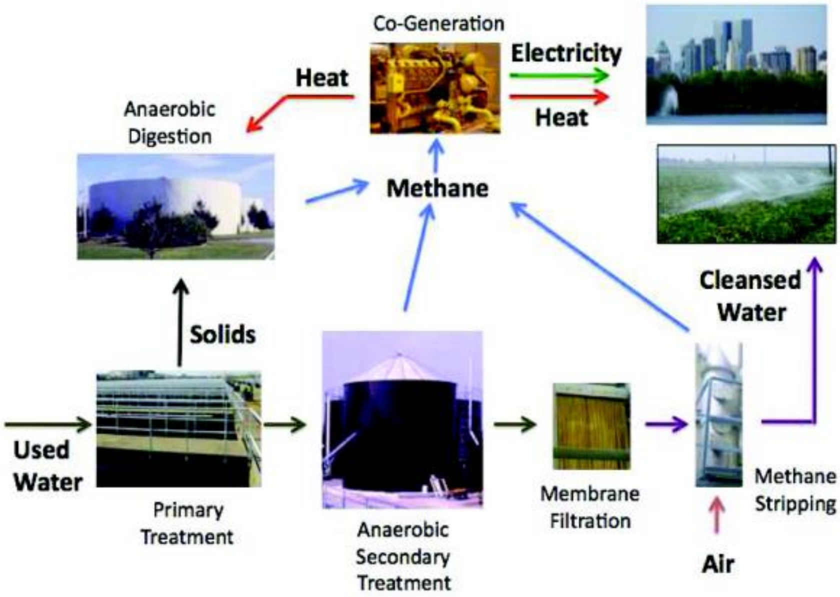

Figure 40 - A hypothetical wastewater treatment system (McCarty et al., 2011)

McCarty et al. (2011) concluded that with a COD value of at least 500 mg/l, the anaerobic water treatment would be a net energy producing process. The COD of the food process effluent in the case study presented in this chapter is 3870 mg/l; additionally since the temperature of the effluent is 28.9°C, it is well suited to microorganism growth. Both these factors strengthen the case for water treatment of the effluent water of food manufacturing facility. In this chapter, the same hypothetical process is considered as in the study by McCarty et al. (2011). The technology is considered that has the benefit of low cost and high rates. In a study using the AFMBR to treat domestic wastewater, with a COD of 500 mg/L at a reactor retention time of 5 hours, the total energy expenditure was 0.058kWh/m^3 while the COD removal was 99% (Kim et al., 2010). For the weekly average effluent flow rate of 4.55 kg/s, the supply electricity amounts to 159.6 kWh/week. The exergy of the treated water is composed of the inorganic content (same as before treatment) and 1% of the organic content resulting in a value of 2010.4kWh/week.

Figure 41 – Estimation of exergy flows resulting from a hypothetical anaerobic wastewater treatment of the food process effluent

7.9. Results:

Through modelling the resources in terms of exergy, the resource consumption in the baseline scenario can be compared with that of option 1 where anaerobic water treatment is employed. Since the water treatment produces natural gas, it can be used to offset the gas supply to the factory. For natural gas, the conversion factor of 1.0387 is used to convert the LHV to exergy values (CIRCE, 2008). The comparison in Table 18 shows that an overall resource saving of 4.1% could be achieved by employing the anaerobic water treatment process.

Table 18 – Estimation of reduction in resource use for a full time working week in 2014 at the food factory

	Electricity	**Nat. Gas exergy**	**Water**	**Total**
	(kWh/week)	(kWh/week)	(kWh/week)	(kWh/week)
Baseline – No treatment	204,434	766478	40,605	1011517
Option 1 – anaerobic treatment	204,434+165.1 =204,599.1	=766479-41,815 =724664	40,605	969869
Reduction in resource use	-0.08 %	5.5 %	0%	4.1%

7.10. Findings and discussion:

The conceptual approach presented in Chapter 4 considers all flows through a manufacturing facility as exergy flows. Therefore, all flows through a manufacturing facility need to be modelled in terms of exergy. This chapter presented the first instance of modelling water flows in terms of exergy in a manufacturing environment and the analytical method was therefore described in detail. A food production facility was studied and possible resource savings achievable through water treatment were estimated. The findings from the study are as follows:

- The water (m^3) and energy (kWh) supplied to the factory were compared in the common units of kWh using the thermodynamic quantity, exergy. This made it possible to compare the resource use due to flows of different nature. Such a comparison would not be possible on an energy and mass based approach.
- The thermal exergy content is 0.03% of the total exergy in the effluent water flow. This is due to its temperature being near ambient thus having very little work potential. Due to the large mass of water flowing through the system, an energy analysis would overestimate the value of the thermal content in water.

- The method of calculation for chemical exergy of the effluent water requires knowledge of basic chemistry which might not suit the profile of a typical energy or resource manager. However, it was found that the chemical exergy of the effluent water in the food process mainly depended on the organic content or the COD value which could be calculated using a simple empirical relationship (equation (7)).
- Water treatment by an anaerobic process is a net exergy producer for COD values greater than 500 mg O2/litre (McCarty et al., 2011). Since the food process effluent had a COD of 3800 mg/L, significant natural gas could be produced from water treatment, which would offset the total resource consumption. This finding can be generalized to the food processing industry as the effluent water has a COD commonly above 1000 mg/L (Chan et al., 2009). With anaerobic treatment the overall natural resource consumption reduced by 4.1%, the natural gas exergy supplied reduced by 5.39% while the electricity required increased by a small amount of 0.08%. For further improvement in resource efficiency, there is a possibility of using the treated water as grey water and as a fluid in the factory cooling systems. The resource saving achievable through implementing such a measure could be explored in a future study that would also undertake a detailed assessment of the water cleansing process and its associated issues. Perhaps the main drawback with anaerobic treatment is the inability to purify the water to an extent that is acceptable for use in the food production line. Chan et al. (2009) reviewed high rate anaerobic-aerobic bioreactors for the treatment of industrial effluent wastewater that produce high purity treated water. Other researchers such as Frostell (1983) also remark that this combination of anaerobic and aerobic digestion presents a great opportunity for resource recovery. If this process is used to purify the water to a satisfactory level, then it could displace a major portion of the water consumed in the facility, of course at the expense of additional resources.

While the approach provides benefits in quantifying resource consumption and comparing technology options, there are certainly limitations to it which are as follows.

- Additional water quality data is required in order to calculate the chemical exergy of the water flow. Increase in data requirements add to the complexity of an approach and reduce its practicality.
- The choice of the reference environment significantly affects the results of the exergy calculation. Additionally, the method is also different depending upon what substances are considered part of the reference environment.

- The use of exergy when modelling the effluent water flow does not represent the toxicity in the flow. This issue has been highlighted by researchers before such as Hellstrom (1997) and Mora (2006) and is a valid criticism of this approach.
- The main component of the chemical exergy in the effluent is due to its organic content. However, as seen from Table 17, there is significant variation in the results through the different methods available. There is a difference of 14.2 kJ/L or 24.5% of the average value among the two different methods which is rather large.
- The resource savings quantified in this study are subject to an assumed hypothetical water treatment process form literature. If accurate resource savings estimation is required, a detailed study for the food manufacturing facility's water treatment can be conducted in the future.

7.11. Chapter summary:

The approach presented in this thesis can be used to compare different technology options available and to quantify the resource consumption in each case. This case study provided a particularly good example of where the exergy based approach could be useful, as it has a large variation in the nature of resource flows. Electricity, natural gas, water flows with a varying chemical composition and heat flows at varying temperatures are all assessed using the exergy based method, thus allowing an objective holistic analysis. The results of chemical exergy calculations and estimations from literature show that water treatment of effluent water in food processes can be a net exergy producer. Finally, the findings were listed together with the strengths and limitations of modelling water flows in a manufacturing process in terms of exergy.

Chapter 8 Qualitative assessment of the developed method

8.1. Chapter overview

A resource accounting approach for factory analysis was presented in chapter 4 and it was illustrated through case studies in chapters 5 – 7. While the previous studies were useful at illustrating the application of the method from a theoretical perspective, this chapter presents an investigation into the practicality of the method. This chapter explores through a qualitative study, the value and effectiveness of the approach in practice for the industry. The views of experts regarding the resource accounting method are analysed from which key conclusions are derived. The following section describes the methodology used, while the subsequent sections present the study itself.

8.2. Method for Data collection:

Initially, the method of data collection chosen was that of interviews, as this would give the opportunity for practitioners to express their views. Due to the technical nature and novelty of the devised approach for factory analysis, a pre-requisite was to explain it to the interviewees before asking their opinions. A presentation explaining the approach was sent to each interviewee in advance so as to give them a chance to understand it. Furthermore, it was necessary to select people to comment on the approach who have enough suitable experience to gauge the value of the approach to industry. Table 19 lists the roles of some of those questioned.

Table 19 - Roles of respondents and interviewees

Serial No.	Respondents and interviewees roles
1	Environmental Programmes Manager at BMW Group
2	Sustainability manager at ABB
3	Global Packaging Sustainability Manager at SABMiller
4	Country Head of Energy & Sustainability at COFELY
5	Group Energy Manager, Imperial Tobacco Limited
6	Assistant Professor, involved with 10 research projects related to

	energy efficiency
7	Expert in industrial energy efficiency implementation and policy (19+ years' experience)
8	Energy auditing practitioner and adviser at Motiva (30+ years' experience)
9	Industrial performance expert at a leading global aircraft manufacturer (14+ years' experience)

The author attended several events and conferences in order to schedule such interviews. The ECEEE (2014) conference series and the CIS (2015) events proved to be particularly useful. Through interaction with the people at such events, 25 experts were identified and invited to contribute, from which 4 were available for interview. A presentation describing the approach in this thesis was sent to the interviewees beforehand and again presented before questioning. The software Skype was used for this purpose as the interviewees were resident in different countries. Additionally, the screen sharing feature in Skype allowed presenting the slides effectively, while recording software recorded all the responses which made transcription accurate. This method of interviewing was very much adequate to achieve the goals of this study, however the number of interviews conducted in this way was felt to be insufficient, so a webinar was conducted in which the approach was presented in detail (Khattak, 2015) . The webinar was attended by academics and industry experts working in the area of sustainable manufacturing. The presentation in the webinar was followed by a question and answer session, which also proved to be valuable in gauging the novelty and value of the approach. The attendees of the webinar were asked to answer an online survey, which formed the second set of data. In order to get further responses, the professional networking online tool LinkedIn (2015), was used to collect responses to the main questions in the interviews, with more than 50 people being contacted in this way. Among the responses received, only five of them had enough detail so as to be considered as data. This method was different from a standard questionnaire in the way that the respondents had the opportunity to ask any questions related to the proposed resource accounting method. Although a greater number of responses would increase the depth of this study, considering the time and resource limitations imposed upon a PhD project, and the fact that the major portion of this research was quantitative; the 11 responses were considered sufficient to address the research question. Summarising, different methods were used to acquire the data, thus the methodology for this study could be classified as multi-method qualitative (Saunders et al., 2011). The table below provides a breakdown of the data collection modes with their respective useful responses from different experts.

Table 20 - Data collection modes with their respective useful responses

Mode of data collection	Number of responses
Interviews	4
Webinar	2
LinkedIn responses	5
Total	11

8.3. Data Organization:

The data acquired through the multi-method qualitative methodology can be classified into written and oral responses. For the written responses, the data were already well organized according to clearly defined questions. However, the interview data needed to be organized first, based on the sub-themes of questioning.

The interview was designed to address the following research question:

"In comparison with an energy based approach, can the newly designed exergy based approach for resource accounting in factories be more effective at quantifying sustainability?"

When addressing this question, the interview was structured to address the weaknesses associated with the exergy method. For example, a prominent exergy practitioner and proponent, Rosen (2002) identified the following questions that need be asked in order to understand the barriers to the implementation of exergy methods,

- Why are exergy methods not more widely used by the industry?
- What can be done to increase its use and acceptance in the industry?
- Is industry's minimal use of exergy method appropriate?
- What steps should be taken to improve the acceptance of exergy methods in the industry?

The questioning guidelines that shaped the interviews are provided in Appendix 2.The interview data first had to be transcribed before they could be organized and analysed. A sample of the transcribed interviews is provided below in order to illustrate how this was done, whereas the fully transcribed interviews are available as Appendix 3.

Table 21 - Sample excerpt from a transcribed interview

Person	**Transcription**	**Notes**	**Code**
Researcher	Could you describe your role and what it entails?		
Interviewee	In relation to energy efficiency, I have been involved in the (word not clear) office, **looking at the implementation of the voluntary agreement scheme and energy efficiency in medium sized companies within France and Belgium**. The companies have to make energy audits looking at energy saving measures they could implement and with some thresholds of economic feasibility. It was my office duty to see that the assessment was thorough enough and also after approval of energy plan that the energy efficiency measures we agreed upon are being implemented or not. For the medium sized companies it was the first time that I had a comprehensively look to energy consumption and a deeper assessment to the possibilities.	Description of role	
Researcher	Could you please explain what type of companies, manufacturing perhaps?		
Interviewee	**They were manufacturing companies and more than one fifth were chemicals and plastics and a large part was of the food industry** and it was also the technology sector, and there was also a part of the textile and wool processing, a part of various **glass manufacturing** companies, also it involved the **printing** industry.		

The notes column was for any comments necessary to aid the understanding of the transcribed text. Pieces of information that were considered important by the author were highlighted in bold. Additionally, the data have been coded based on techniques described in standard texts such as (Tracy, 2012). The codes were assigned based on the interview structure, and are shown in **Error! eference source not found.**.

Table 22 - Text coding table for the transcribed interviews

Code	Questioning sub-topic
01	Understanding and importance of manufacturing sustainability
02	Treatment of mass and energy flows at a factory
03	Drivers for sustainable manufacturing
04	Receptivity of the general exergy concept
05	Utility of the exergy concept in the context of factory analysis
06	Usefulness of the exergy based holistic analysis approach

07	Barriers to its practical application
08	Drivers for its practical application
09	Suggestions for improvement

The codes helped extract the relevant parts of the interviews that made that analysis easier to conduct. This job could have been performed using software such as Nvivo for qualitative data analysis (Bazeley and Jackson, 2013), however due to the relatively small number of interviews a manual approach sufficed. Once the data were transcribed and organised, analysis could be carried out. The following sections describe the analysis based on the sub-themes of questioning.

8.4. Analysis:

The utility of the approach for the industry depends upon several factors. The questioning was designed to inquire about each factor to gain an understanding of the overall utility of the approach and to identify the barriers to and drivers of its practical implementation. To this effect, the analysis is conducted based on the following themes:

i. Understanding and importance of sustainable manufacturing.
ii. Utility of the proposed factory analysis approach for the industry.
iii. Barriers to its practical implementation.
iv. Drivers of its practical implementation.

Each theme is now analysed separately:

8.4.1. Understanding and importance of sustainable manufacturing:

Sustainability is a broad term therefore sustainable manufacturing can mean different things to people with different backgrounds. The view taken in this research is that resource efficient manufacturing directly translates into sustainability in the factory. A similar view regarding the definition of sustainable manufacturing was shared by interviewee #3, who is an experienced academic with an energy auditing background,

> *"The definition of course is that manufacturing that is as resource efficient as possible."*

This feedback reinforces the view taken in this thesis, and is considered an acceptable definition of sustainable manufacturing. The views of the experts interviewed suggest that sustainability in manufacturing is quite well understood. For example, upon asking this question from interviewee

#1, who was overseeing the implementation of energy audits in around 200 manufacturing facilities across Belgium and Europe, he replied

"I would say in general, it's quite well understood, because we have been talking about sustainability with these aspects with more than a decade by now"…

He further added later, *"it is quite developed in places more than a decade by now and I have the feeling that it is generally accepted."*

A good understanding of sustainable manufacturing is considered important to the justification of the holistic exergy based approach presented in this thesis. From the interviews, there seemed to be a consensus among the experts. The dominant opinion was that sustainability in manufacturing is a second goal after the primary goal of product manufacturing and financial gains is met. For example, interviewee #3 said,

"I think, the first, most important thing is the quality of the products, and then after quite a big gap, comes energy efficiency. Sustainability is at the same level as energy efficiency, material efficiency and so on, but the first priority is the quality of the product."

The responses from the interviewees in this section were based on a scale of 10, one being 'not important at all' and ten signifying the 'most important'. If the importance of sustainability in the industry was considered by the experts to be conditional on achieving economic gains, then the scaled response had an asterisk (*) following it. Table 23 shows these results, the unconditional importance of sustainability in manufacturing on average being given 3 points on the scale of 10. It is interesting that if improved sustainability can bring about financial gains, then its importance increases to 8 – 9 on the scale of 10. Consequently, interviewee #2, with 30+ years of experience in industrial energy efficiency, said in his concluding remarks:

"And first as I mentioned… money talks..."

While the incentive of financial gains is certainly a driver for sustainable manufacturing, as indicated by the results in Table 23 show, it might not always be the case. Interviewee #3 had an interesting view:

"I think the answer is very contextually based, because in Japan, they don't see their company or themselves as the major emphasis, they see their country. So, if you ask a Japanese researcher, he or she would say that, it's all about the social aspect and the nation-wide aspects for that country. That is why so much emphasis is on context. I have never faced this in Europe and absolutely not in Sweden…"

For this reason, the same person gave a third of the points from a total of 10 to each of the three aspects of manufacturing that drive sustainability. It must be noted here that Table 23 has information from only three interview responses. This initial question about the importance and understanding of sustainability in manufacturing was not asked in the other modes of data collection. Instead the written questions were few in number so as to have a greater focus on the other 3 themes that were considered to be of greater importance to the research. If the limited data in Table 23 **Error! Reference source not found.**is considered to be an indicator of expert views, then t could be argued that sustainable manufacturing is well understood in the industry; however it is relatively less important than production. Additionally, economic gains certainly drive sustainability in manufacturing, but social or environmental aspects may dominate depending upon the context.

Table 23 – Importance and drivers for sustainable manufacturing

S. No.	Person	Environmental	Social	Economic	Importance
1	High level Energy audit overseer	2	2	6	3, 8/9*
2	Energy audit practitioner with extensive experience	2	2	6	3-4, 8*
3	Academic/industrial energy efficiency practitioner	3.33	3.33	3.33	3

** Importance of sustainability in manufacturing provided they can bring financial gains*

8.4.2. Utility of the novel factory analysis approach

In the interviews and webinar, first the proposed approach was presented in detail. The factory resource accounting method in this thesis combines two concepts: exergy analysis and holistic view of a factory. Therefore the questioning proceeded along these lines. A relevant excerpt from the conversation with interviewee #1 is shown in Table 24.

Table 24 - Comments of interviewee #1 regarding the exergy based holistic approach's utility

Researcher	**Can you comment on the holistic nature of the approach? Would it be Beneficial or not?**	
Interviewee	Yes I think it would, I think it has been used in another way in the pinch approach….	(The interviewee continues to identify some barriers to its implementation)
Researcher	Why would you think it is necessarily beneficial to take a holistic approach?	
Interviewee	Well, I assume it makes them aware of the possibilities of saving energy.	
Researcher	Could you comment on the suitability of an exergy based approach with regards to identifying surplus	

	resources in a factory, in comparison with an energy based approach?
Interviewee	If it's as easy to implement as an energy approach, then I don't see much hindrance in using it.

From the above conversation, one can see that the approach presented in this thesis was considered beneficial for the industry; however the interviewee was quick to expand on the barriers to its implementation. This tentative agreement about its utility was a recurrent theme in all the interviews conducted. Below are the relevant parts of the interviews number 2 and 3.

Table 25 - Comments about the utility of the factory analysis approach by interview #2

Researcher	**Do you think this holistic approach would give you clearer insights into resource savings for a factory?**
Interviewee	Yes, yes I think this exergy gives this view what is left of the energy and how the surplus heat can be used in a different integration with parts. It is not that clear when you do some changes, it all for the best, but like in this jaggery case, it was kind of surprising how this picture changed when you deal with exergy.
Researcher	Do you think when you are looking at the whole factory holistically on a common unit basis it would have any benefits or would it be more beneficial to keep these separate? For example it might yield a combined indicator however some people might want to keep them separate.
Interviewee	Hmm… I think it would be better to combine because then you see the whole thing at one time than if you take them in two parts then it's kind of what is happening here, what is happening there, and you don't know how they combine together. Especially in the food area I think, there might be some interesting cases where this would be useful, because there are quite low temperatures, then there is steam, then there is cooling water, all this baking and boiling and what is happening in the ovens, and this surrounding might be interesting for this type of study.

Table 26 - Views of Interviewee #3 regarding the utility of the devised factory analysis methodology

Researcher	**Do you think a holistic approach is useful in this regards as well?**
Interviewee	Yeah – absolutely. A great yes. Including both laws of thermodynamics, I mean that should almost be written in stone, when it comes to sustainability. You are comparing Japanese yen with dollar bills, you are just speaking about money and you are missing out on value.

The collective feedback from the interviews, LinkedIn (2015) responses and questionnaires regarding the utility of the devised methodology for factory analysis is presented in Table 27. For the questionnaire, it was not possible to describe the approach beforehand. Therefore, the questions were formed in a different way to that of the interviews and webinar. As one of the main consequences of the devised methodology was a thermodynamics based unified indicator for factory analysis, the use of such an indicator was enquired about rather than the approach itself.

Table 27 - Results - Utility of the factory analysis approach for the industry

Responses after detailed presentation of the factory analysis methodology			
	Person	Q: Holistic approach of combining mass and energy flows useful?	Used exergy concept before / has a current understanding of it
1	Interviewee # 1	Yes	Yes
2	Interviewee # 2	Yes	No
3	Interviewee # 3	Yes	Yes
4	Interviewee # 4	Don't know	No
5	Respondent # 1	Yes	No
6	Respondent # 2	Yes	Yes
Written responses			
	Person	Unified indicator useful	Used exergy concept before / has a current understanding of it
1	Environmental Programmes Manager at BMW Group	No	no
2	Sustainability manager at ABB	No	Yes
3	Global Packaging Sustainability Manager at SABMiller	Yes	No
4	Head of Energy & Sustainability at COFELY UK GDF-SUEZ	No	No
5	Associate Director at CorEnergy Limited	Yes	Yes
6	Survey respondent # 1	Yes	No
7	Survey respondent # 2	No	Yes
8	Interviewee #4	No	No

Based on the interviews and survey data, the major findings with regards to the utility of the approach for the industry were,

- Of the 5 people that were asked the question about the use of the holistic approach, all agreed it would be valuable for the industry.
- Of the 6 people to whom the exergy based holistic approach was presented in detail, 5 said it could be useful to the industry and their organizations, while one was unsure.

From the written responses, the major findings were,

- Five of the seven respondents were not in favour of a 'single' unified indicator.
- Of the three respondents in favour of a unified indicator, only one had used exergy.
- Of the people who thought a unified indicator based on exergy would not be sufficient for indicating the sustainability level of a company, 2 out of 5 used the exergy concept before.

The findings listed above suggest that while viewing the factory holistically and using the exergy approach can be useful, using a single indicator for measuring sustainability of a factory is not desirable. Additionally, 5 out of the 11 respondents/interviewees had current working knowledge of the exergy concept. This shows that with people experienced in energy efficiency and sustainability in manufacturing, exergy is not a foreign concept.

While these findings are encouraging, strong barriers were identified that impede the application of the proposed method. For the approach to be applied in practice and perhaps to benefit the industry, it is therefore very important to identify the barriers and drivers to its practical application.

8.4.3. Barriers to practical implementation:

From the data collected, the major barriers identified were lack of familiarity with the exergy concept, complexity of the procedure and pricing of resources without consideration of energy quality. For example, interviewee #1, who was overseeing an energy audit of around 200 manufacturing sites in Belgium and France, said:

"Well, just from a practical point of view, I see people struggling with the energy concepts in a factory and how can they deal with exergy aspects, so, I think from a practical point of view, it is very challenging."

This challenge of less familiarity with the exergy concept is linked with the complexity associated with conducting an exergy analysis. Interviewee #1 had the following to say in this regard:

"It's beneficial, but practically, you are a bit limited because of the complexity. And I am not sure that you can apply it so widely as an energy audit. You need energy auditors who can understand the

concept and who can easily implement the methodology in the different cases they are confronted with, and I am a bit sceptical about that."

As mentioned before, the pricing of resources presents an issue as well. Even if the approach is applied in practice, this is an issue that goes beyond the scope of thermodynamics. While the exergy approach can be good at quantifying the value in resource flows, pricing may not always follow accordingly. Below are some comments of the interviewees relevant this topic,

"The analysis of exergy, with energy quality and quantity is inhibited to a large extent by the fact that we pay for quantity, not for quality. Energy quantity is used in an audit, in the core reporting to the company, quality is hardly ever covered. The (exergy) concept is just rock solid, but when it comes to application in the real world, it is not a lot of value (economically). The whole system of valuing energy and not its quality of course needs to be reformulated and that is a political issue that I am very doubtful it will ever happen." (Interviewee #3)

"That is one of the main barriers I do see. In general, one can say the higher the quality, the higher the price. But this is not always the case, as at some points, power can be cheaper than natural gas. In the city of Keul, they started inserting electric boilers within the heating grid to replace natural gas. So they are using electricity to heat up water to 100 degree Celsius, which is not very exergy efficient. But from an economical point of view, there was so much wind power that they really needed to discharge it, so they could use it to heat up water at very low prices." (Interviewee #1)

This comment shows that value is not always allotted based on the exergy content of flows, however it is also true that using renewable electrical exergy to heat water, however exergy inefficient reduces the proportion of non-renewable exergy usage. This agrees with the conceptual approach presented in thesis which uses non-renewable exergy consumption as an indicator for resource consumption. Table 28 below presents a collection of all the barriers identified by the respondents to help extract the major ones.

Table 28 - Barriers identified to the practical application of the factory analysis approach

Person	Barrier identified
Interviewee #1	• Industry people struggle to understand energy, exergy aspects is going to be practically more challenging • Resources are not always priced in consideration of energy quality • Practically limited due to complexity, e.g. exergy allocation due to products • Time consuming method

	• Additional incurred costs
Interviewee #2	• People sticking to old habits • Time consuming • Additional costs • Low understanding of the exergy concept
Interviewee #3	• We pay for energy quantity, not quality and therefore energy audits are designed this way • Lack of economic value • Deployment of insights gained • Lack of understanding in education system (which is not likely to be addressed) • Barriers to its application might change, depending on the location.
LinkedIn(Environmental Programmes Manager at BMW Group)	• Combining mass and energy flows results in too few key target metrics, making targeted reduction difficult
LinkedIn(Sustainability manager at ABB)	• Single indicator can be misleading
LinkedIn(Country Head of Energy & Sustainability at COFELY)	• Unified indicator reduces flexibility in choices available to clients.
Survey Respondent #2	• Single indicator does not provide enough detail • Low understanding of energy concept by the industry • Energy is typically a low expenditure for companies, as compared to others.

Using the above table, the following distinct barriers were identified,

1. Lack of understanding of the exergy concept
2. Pricing of resource does not always consider resource quality
3. High complexity of analysis method
4. Time consuming
5. Additional costs
6. Actual deployment of gained insights
7. People sticking to old habits
8. Measuring sustainability with a single indicator does not provide enough detail and flexibility

These barriers being recognised, suitable means to overcome them needed to be identified as well. Therefore, the final section of analysis deals with the drivers that could possibly make the approach presented in this thesis useful for the industry on a large scale.

8.4.4. Drivers for practical implementation and suggestions:

The complexity of the exergy concept, the lack of understanding among practitioners and the time/cost demands are all related issues. Respondents and interviewees identified some means through which these could be possibly overcome. Following are the comments of interviewee #1:

Table 29 - An excerpt from a discussion with an expert about overcoming the barriers of difficulty in understanding the exergy concept – Part 1

Researcher	**Could you comment on the suitability of an exergy based with regards to identifying surplus resource in a factory, in comparison with an energy based approach?**
Interviewee	If it's as easy to implement as an energy approach, then I don't see much hindrance in using it.
Researcher	Do you think a step by step exergy audit methodology which an auditor or factory manager could apply would be beneficial in terms of adding value to the approach?
Interviewee	Yes – if you could demonstrate it practically
Researcher	Could you expand on this please?
Interviewee	Because you are in direct contact with personnel form companies themselves, you could understand what motivates them to test it. And how this methodology might respond to their needs.

The above conversation suggests that if the method developed in this research project is somehow moulded into an easy to apply form, then companies might consider using it. Interviewee #2 commented on this issue as well, and identified a need for learning the exergy concept at educational institutions. In response to a question regarding the utility of the presented approach, the interviewee added,

"But if it's taught in universities or when studying (before university) would learn what are the insights of this thing then when they are in work life etc. they would have the basic knowledge of this thing, I would be much easier to present these results for them."

Later in the interview, a similar comment was made.

"I think there should be some public seminars where exergy audits and exergy is presented and people get to know what is behind this word."

Interviewee #3 had very interesting views, and provided useful suggestions to overcome the identified barriers. A relevant part of the interview is provided below,

Table 30 - An excerpt from a discussion with an expert about overcoming the barriers of difficulty in understanding the exergy concept – Part 2

Researcher	**So if these insights are there, why isn't the industry acting? How could we effectively introduce the concept of exergy in the industry so that the insights could be converted into some action?**
Interviewee	Well, if I would have answered this question, say ten years ago, I would have given the answer which is the most common answer given by engineer, policy makers and economists. That is to provide information campaigns, raise awareness and then things change. But if you are to gain cultural transformation, for any concept, it always starts with the theory and education. In this case, most manufacturer, they don't even know what exergy is, so I think having to introduce it effectively, firstly would be to include it in the school system. Not only energy, but exergy, not only at university level, but in elementary school and onwards. Secondly, the whole system of valuing energy and not its quality of course needs to be reformulated and that is a political issue that I am very doubtful it will ever happen. But then, that would also have to be taken into account or the research community needs to develop methods so that, when we speak about sustainability, we don't only speak about quantity but also about quality. That could also develop the methods, for example, the methods today don't apply quality so these two issues

Addressing this same issue, Interviewee #3 identified a possible future academic study to this thesis as follows,

"One further study to be done within the UK, having a questionnaire rather than having semi-structured interviews, asking, guys why you are not deploying exergy. That could provide some insights, but really it would be for academics, than changing or increasing the use exergy analysis."

Table 31 lists all the drivers identified through the interviews and written responses. The major distinct ones are summarized as,

1. If somehow its application could be made easier, its practical application in the industry could improve.
2. More examples of practical case studies, to engage the industry
3. Educate students and practitioners
4. New methods that use the 2nd law of thermodynamics for measuring sustainability
5. A step-by-step guide for exergy auditing would help reduce the practical complexity of conducting such an audit.

Table 31 - Drivers for the practical application of the devised approach to factory analysis

Person	Driver identified
Interviewee #1	• If it is easy to implement, then not much hindrance to it • Practical demonstration to engage the industry
Interviewee #2	• Teaching the concept within the education system • Good for application in industries with large variation in energy quality and water consumption e.g. food production • Public seminars that present exergy audits
Interviewee #3	• Methods and tools that incorporate the 2nd law of thermodynamics in sustainability analysis • Step-by-step exergy audit methodology would help acceptance and practical application of the concept • A study to investigate the barriers to implementation of industrial exergy analysis in the UK.
Global Packaging Sustainability Manager at SABMiller	• Increasingly our stakeholders are keen to find a tangible numerative measure for sustainable development activities
Associate Director at CorEnergy Limited	• that it would be an excellent way of demonstrating full-life cycle production efficiency and to identify areas for improvement
Survey respondent #1	• It helps in waste management

8.5. Summary:

This chapter presented a qualitative study of the practical utility of the factory resource accounting approach described in this thesis. Based on the results from the analysis in this chapter, the following main conclusion was derived,

The results show that taking a holistic view of a factory is certainly beneficial for resource accounting methodologies. Also, a dominant view among the experts was that the exergy based factory resource accounting methodology has good potential to benefit industrial sustainability. However, the experts also agreed that exergy was too complex a concept to be currently widely applied in practice.

In order to address this concern, the experts identified drivers that could help improve the practical utility of the developed approach. Among the drivers, the following were practical means that could lead to the practical application of the approach presented in this thesis.

- Tools/methods that make its application easier.
- A step-by-step exergy audit guide that allows easy application of the method.

These two ideas feed into the future work section of this thesis, and are further described in the following chapter. Finally, it should be noted that in presenting the approach to experts in a range of settings, the method was exposed to high calibre academics in the area of sustainable manufacturing. In all these interactions, the novelty of the devised factory resource accounting methodology was not in question. This support the author's claim of an original contribution to knowledge made through the research presented in this thesis. The following chapter summarizes and concludes the work done in this research project. Possible future research directions are also identified that would build upon the work done in this project and potentially yield fruitful solutions for industrial sustainability.

Chapter 9
Conclusions and future work

9.1. Introduction:

In a world with depleting natural resources and their increasing demand for the industry, sustainable manufacturing is a desirable goal. Methods that account for resource consumption in a factory are valuable in this regard, as they inform decision makers about the actions that must follow in order to maximize resource efficiency. Based on a review of literature (Chapter two), a knowledge gap was identified in this area of science which is repeated as follows,

Compared to an energy based approach, can an exergy based approach that is based on a holistic view of manufacturing systems be more effective at quantifying resource consumption?

The work that followed the literature review was therefore designed to comprehensively answer the above question. This chapter shows how the above research question was answered and attempts to tie together the findings generated, so that a holistic conclusion about the work can be formed. The strengths and limitations of the work are highlighted and avenues for future researched are also presented.

9.2. Short summary and conclusions:

In response to the previously mentioned research question, a methodology for resource accounting in factories that combined exergy analysis with a holistic perspective was developed. The resulting novel concept was illustrated in practice through three practical case studies of a varied nature, and provided cases for quantitative validation of the developed method. This was followed by a qualitative study that enquired from experts about its practical utility for the industry. The strengths and weaknesses of the conceptual method that were identified and the research's limitations in general are listed below:

9.2.1. Strengths:

1. In comparison with a mass and energy based approach, the consideration of energy quality in the exergy concept allowed generating results better representative of reality.

Taking the example of case study 1 (the engine production line), the energy based results attributed significantly greater resource saving value to heat recovery as compared to the PV retrofit option. The energy approach exaggerated the resource savings achieved through heat recovery, this relating to its inability to account for energy quality. On the other hand the exergy based results suggested almost equal resource savings for the two options. Another example is that of case study 3, where the energy approach again overestimated the value of low grade thermal energy in effluent water from the food production facility.

2. In using the exergy concept, all flows can be modelled in the same physical units, thus providing a better opportunity to analyse resource savings in a holistic manner. This aspect of the developed approach was evident in case study 3, where a possible water treatment process could result in both reduced energy and water usage by the food factory. Through modelling of water flows in terms of exergy, the possible resulting savings in resource consumption was estimated to be 9%, thus allowing a holistic analysis.
3. The exergy approach can result in extra information that can provide deeper insights into resource consumption in whole systems; this was illustrated in case study 2, where exergy destruction served as an indicator for absolute waste rather than surplus that is wasted. The exergy destruction in the process was due to (i) changes in chemical composition of sugars present in the juice (ii) combustion in the furnace. Improved efficiency due to lowering the process operating temperature increased the proportion of exergy destruction due to combustion, that had an unwanted side effect if potential industrial symbiosis.
4. The work presented in this thesis is a step towards furthering our understanding of resource consumption in buildings through the exergy concept. It attempts to extend the state of the art by modelling water and other chemical flows in addition to energy flows. To the author's knowledge, sustainability assessments of buildings based on exergy do not model water consumption. An example being a relatively recent thesis by Jansen (2013) that presented a detailed study about the use of exergy in the built environment, confirming the before mentioned point.
5. Based on the results of the case studies and views of practitioners and experts in the field, the developed factory resource accounting methodology has good potential to be practically useful for the industry.

9.2.2. Weaknesses:

1. The major weakness of the developed approach was due to the increased complexity and effort in conducting an exergy analysis, as compared to energy based methods. Particularly, for its

application to manufacturing in general, the variation in manufacturing designs can make its application difficult, and may require specialist knowledge. Such an effort also incurs time and cost expenditure, and therefore its application must warrant the use of these additional resources in comparison with an energy analysis. This major drawback was also highlighted by the qualitative assessment of the devised methodology, and remains a weakness to be overcome.

2. The reliability of exergy analysis is susceptible to the selection of the reference environment composition. This fact was highlighted in jaggery process case study, but more so for the water reuse study. The modelling of water in terms of exergy depends on a number of factors that are described in detail in chapter 7. For example the concentration of salts and organic matter considered to be present in the reference environment impact the generated results greatly.
3. Exergy is essentially a measure of variation of a mass or energy flow from a dead (useless) state. It can be argued then, that greater the exergy, the greater it's potential to impact our natural environment. This argument although logical, does not always stand true in practice. This issue was presented theoretically in the literature review section of this thesis, which also resurfaced in water reuse study (chapter 7). Any exergy due to the toxic matter in the effluent water would be a small fraction of its total exergy content, and therefore misrepresents the impact it could have on the environment. A similar issue is observed with indicating the value of minerals, detail provided in chapter 2. It is concluded that the exergy concept must be used with care if environmental impact indicators are to be developed on its basis.
4. While the research design included a variation among the case studies and the qualitative assessment of the work attempted to comprehensively test the application of the developed method in general, complete generalization to all manufacturing processes is not claimed. Such a claim, if even possible, would require illustration of the approach to a larger set of case studies which was not possible due to time and resource limitations imposed upon a PhD project. For the same reason, the small data set acquired in the qualitative analysis section detracts from confidence in the emergent themes identified

9.2.3. <u>Contribution to knowledge:</u>

The work that was carried out in this research project resulted in a scientific contribution to knowledge that includes,

a. A novel exergy based approach to resource accounting in factories was devised (Chapter 4). This approach extended the previously developed industrial ecology model of a factory by incorporating the 2nd law of thermodynamics through the concept of exergy. It presented a conceptual model that views the factory as an integrated system of production processes and the building, where modelling of all flows and estimation of resource consumption is done through the exergy concept. Three case studies illustrated how the novel approach could be applied to varied manufacturing environments in practice.
b. The first exergy analysis of a jaggery making process was presented.
c. The 3rd case study (a food factory), presented the first example of modelling water resources in terms of exergy for a manufacturing system.

9.3. Recommendations for future work:

The future research avenues identified through the course of this PhD research project are given as follows,

9.3.1. A software tool:

The encapsulation of the resource accounting method in an easy to use software tool could address a number of its weaknesses. With a user friendly interface, it could overcome a major barrier in its widespread application by reducing the time and effort required to implement it. Furthermore, it could take into account the dynamic changes in weather conditions to yield reliable exergy based results. Within the UK, research along these lines is being conducted at the energy institute, UCL London. For example Kerdan et al. (2015) developed python-based plugins for energy plus that allows automated exergy analysis of seven generic building types. While the tool is a step forward towards automatic exergy analysis, it does not account for all resource flows. An example being that of water flows through a facility, where the thermo-mechanical portion would only be taken into account. Adding such a capability into the tool could allow a more holistic analysis of resource consumption in factories.

9.3.2. An exergy audit guide:

Following the previous idea, at the manual end of the spectrum, a basic exergy audit guide could help energy auditors and like practitioners to apply exergy analysis practically. A great challenge to this would be balancing the complexity and reliability.

9.3.3. Sustainability in the built environment:

The exergy concept could be used to assess the resource consumption in the built environment. The novelty of this proposed research would be to incorporate the consumption of resources due to non-energy flows, building upon the work presented in this thesis.

9.3.4. Understanding buildings control systems:

Following on from the previous topic of future research, the performance of building environmental control systems can be assessed through the exergy concept. The article by Shukuya (2009) is an example of such work, and may be extended to the application in factory buildings.

9.3.5. Exergy based indicators for resource consumption and impact:

While the exergy concept has been explored to develop environmental impact indicators, the work in this thesis could be used to developed holistic resource consumption indicators that take into consideration non-energy flows. Perhaps a small set of indicators that combine exergy indicators with others might be beneficial to the understanding of environmental performance of factories.

9.3.6. Barriers to the implementation of exergy analysis study:

A short study was conducted towards the end of this research project in order to investigate the practical utility of the exergy based approach. A study that is perhaps based on a survey or a questionnaire rather than semi-structured interviews like in this thesis, might attract a greater number of responses. The larger data set could then be analysed to understand the drivers and barriers to the practical implementation of exergy analysis within the UK. It is important to note that the results of such studies are susceptible to the geographic location of the study, as different cultures and economies have different motivations for improved sustainability.

9.4. Final conclusion:

The work presented in this thesis advanced the state of the art in analysis techniques for resource accounting in factories. It brought together varied concepts and techniques and is a step in the direction towards effective resource accounting in manufacturing. It combined buildings exergy management with exergy analysis of production processes in order to progress towards a holistic understanding of resource efficiency in factories. Both the quantitative results and views of experts in the field show that the method developed has good potential to benefit industrial sustainability. However, the use of the exergy concept involved unwanted complexity that impedes its widespread application in the real world. A possible means to overcome this limitation is the development of a computer based tool that could reduce the complexity and effort needed to apply it in practice. Such a tool could overcome the weaknesses of both energy and exergy analysis; and help sustainability practitioners to arrive at better decisions to maximize resource efficiency in factories.

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Appendix 1

This appendix provides the mathematical derivation of exergy and is intended to supplement section 2.5. For a closed system, the 1st law can be mathematically stated as (Tai et al., 1986),

$$dQ = dU + dW$$

Separating the total work done into *P V* work and other work (W'), and then solving for other work yields,

$$dQ = dU + dW' + d(PV)$$

$$dW' = dQ - dU - d(PV)$$

The 2nd law of thermodynamics as stated in the form by Clausius is written as,

$$dQ \leq TdS \; (entropy\ eiher\ remains\ the\ same\ or\ increases\ as\ heat\ flows)$$

Replacing dQ in the 1st law equation derived before with this 2nd law equation gives,

$$dW' \leq TdS - dU - d(PV)$$

If the system is a reversible system, the inequality converts to an equality and gives the maximum work obtainable from an irreversible system.

$$dW_{max}' = TdS - dU - d(PV)$$

Since enthalpy is defined mathematically as,

$$dH = dU + d(PV)$$

Replacing this in the previous equation yields,

$$dW_{max}' = TdS - dH$$

Since the Gibb's free energy at constant temperature is defined as,

$$dG = dH - TdS$$

$$dW_{max}' = -dG = TdS - dH$$

Or after integration,

$$\Delta W_{max}{}' = -\Delta G = T\Delta S - \Delta H$$

That is, for a constant temperature process, the maximum work obtainable from a system is equal to the Gibb's free energy change. If a system undergoes a process in the reference environment and reaches equilibrium with the environment, then the maximum work obtainable, by definition becomes the exergy of the system and is given as

$$\Delta W_{max}{}' = Ex = T_0(S_0 - S) - (H_0 - H)$$

Or

$$Ex = (H - H_0) - T_0(S - S_0)$$

This equation describes exergy mathematically where the properties with subscript zero denote the properties at the reference environmental conditions (the thermodynamic equilibrium state).

Appendix 2

This appendix provides the structure of the semi-structured interviews referred to in chapter 8.

Table 32 - Questioning guideline for the interviews

Sr. No.	Theme/Question
1	Your role and what does it entail? Does your role involve sustainability assessments? If so, how?
	Understanding and importance of sustainable manufacturing:
2	How would you define sustainable Manufacturing?
2 (a)	In your experience, how important and clearly understood is this concept. What seems to be the most important trend in sustainable manufacturing? Could you scale on a range of 1 – 10?
3	If it is important, is it clearly understood? If it's not, then why?
4	In your experience, when looking at resource efficiency, are mass and energy flows considered separate entities or interdependent?
4 (a)	What tools if any, do you use for mapping flows of energy and materials?
5	Weighting of economic, social and environmental drivers for sustainable development.
	Description of methodology and case studies:
	Describe the devised resource accounting methodology along with the case studies. This was done through presentation of the slides describing the content (sent to the interviewee well in advance).
	Exergy acceptability, practicality, application
6	Scale, how understandable do you find the concept of exergy?
7	With regards to identifying resource saving opportunities, how would you compare analysis approach bases on (i) energy quantity (ii) energy quantity and quality?
8	Do you think **this** holistic approach could give clearer insights into sustainability assessments of a factory? If no/yes, why?
9	How would you comment on the suitability of **this** exergy based approach with regards to identifying opportunities for surplus resource reuse within the factory as compared to an energy based approach?
10	Do you find it would be as easily implemented as an energy based approach? If no, how does the difficulty compare?
11	If **this** method is applied in your organization, in your opinion could it bring useful insights? Any examples?
12	If you think it's useful, how do you think it can be introduced effectively into manufacturing industry?
	Suggestions and future research leading questions:
13	Any suggestions for improvement?

Appendix 3

This appendix provides the transcribed interviews that were used to conduct the qualitative study in chapter 8.

Interviewee #1:

This interviewee was directly involved with practicing and overseeing energy efficiency in the industry for France and Belgium, with almost two decades of relevant experience. The transcription is as follows,

Table 33 - Interview #1 transcription

Person	Transcription	Notes	Code
Researcher	Could you describe your role and what it entails?		
Interviewee	In relation to energy efficiency, I have been involved in the (word not clear) office, **looking at the implementation of the voluntary agreement scheme and energy efficiency in medium sized companies within France and Belgium**. The companies have to make energy audits looking at energy saving measures they could implement and with some thresholds of economic feasibility. It was my office duty to see that the assessment was thorough enough and also after approval of energy plan that the energy efficiency measures we agreed upon are being implemented or not. For the medium sized companies it was the first time that I had a comprehensively look to energy consumption and a deeper assessment to the possibilities.		
Researcher	Could you please explain what type of companies, manufacturing perhaps?		
Interviewee	**They were manufacturing companies and more than one fifth were chemicals and plastics and a large part was of the food industry** and it was also the technology sector, and there was also a part of the textile and wool processing, a part of various **glass manufacturing** companies, also it involved the **printing** industry.		
Researcher	So quite a broad range…		
Interviewee	Yes, it was quite a broad range as the agreement was not sector specific as in some countries they have sector specific voluntary agreements but in France it’s not the case.		

Researcher	So did you only look at energy efficiency or did you also look at resource efficiency? Mass flows as well or only the energy part?		
Interviewee	Only the energy part, as it was the topic in the voluntary agreement although it was researched also that, especially if you could minimize waste generation in the food chain and but it (not clear) …		
Researcher	Basically, this interview is divided into two parts, the first one is some general questions about sustainability in manufacturing and the second part is specific to my approach. The first question is, in your view, how would you define sustainable manufacturing?		
Interviewee	In a practical point of view**, if you can maintain these activities for centuries** then its sustainable and they have to stop of course when the markets changes, then of course the products have to change, of course if you can't continue then you have too many other (not clear) of your… (not clear)		01
Researcher	Do you think sustainability as it's understood, is it something important because you are dealing with companies who are dealing with energy efficiencies, and was it something which they thought it was important?		
Interviewee	Your question is about the role of energy efficiency in relation to the sustainability of a company?		
Researcher	I am trying to gather where does sustainability stand in the industry from a practical view point, do they really consider it something in which they will invest time in it, and how important is it on a scale of one to ten, how do you think in your experience, how important is it for the management in manufacturing?		
Interviewee	Sustainability for a purely environmental point of view might be limited, companies want to survive and if its effects the chances of survival, or even enhance the survival chances then they look at it very carefully and also it has a negative effect, (not clear), can do something about it , then it does not have any effect on the chances of survival and if the chances of survival metric is financial then there is not much attention to it.	Not very clear in these lines	
Researcher	So you think it is driven mostly be economic gain, and not necessary by environmental?		
Interviewee	Yes, yes, yes… for sure. And well (not clear), for instance over here we are in a process in which companies are looking at new energy sources and in this area they are trying to develop deep (not clear) in which we could tap		01

	water from deep subs far(not clear word), …. And the temperature of the place is 125 degree Celsius and they are looking into various ways to use that heat source and into the companies the main motivation, of one company is part of an international group is saying we need to sustain our activities here and if we have a lower energy bill as compared to the competitors, it gives us better chances for survival.	
Researcher	I know it must be difficult to put it on a scale, but could you scale its importance on a scale of one to ten	
Interviewee	**Sustainability purely for environmental reasons, I would say rather low, 3 to 4**, but sustainability (not clear), financial balance of the company then much higher.	01 03
Researcher	So if you look at all the three aspects of sustainability, social, environmental and economic, then… what figure would you put to them?	
Interviewee	Well, **the financial from the point of view of the companies, dominates, I would say 7 points**, (recording missing a bit)	03
Researcher	From manufacturing, and you said that if you purely consider it as a environmental action, it is 3-4, and then you said that if you weigh in the financial then it is higher, so on a scale of one to ten, how much higher would it go then.	
Interviewee	**Eight or nine.**	03
Researcher	OK	
Researcher	So now since, you yourself have elaborated on two aspects of sustainability, do you think these aspects are understood in a manufacturing firm or is it not?	
Interviewee	I would say in general, it's quite well understood, because we have been talking about sustainability with these aspects with more than a decade by now and also the chamber of commerce did some work on sustainable manufacturing and I do know what definition they used, has been welcomed, also by industry, the environmental regulations they have to comply with and **its quite developed in places more than a decade by now and I have the feeling that it is generally accepted.**	01
Researcher	Do you think that mass and energy flows should be considered separate with regards to efficiency or do you think they are interdependent entities?	
Interviewee	Hmm.. as far as I can see, well , I am confident as I see the energy flows, I do not think that there is a systematic way to look at mass flows within a company and there is waste regulation also as waste generates costs, that is	02

	something they are directly confronted with, discharging the waste. I think they are not that much aware of the cost related to generating the waste. Because if you have a product, which does not comply with the quality standards with what it should have, then you have waste. Even in the whole process, you to put resources to it, and energy and mass resources to produce, so that's a loss, and are not quite aware. **I don't think they are much aware of the waste generated over here, no framework, to look into that,**	
Researcher	So just to confirm, you said there is no systematic framework, so are you aware of any tools which they use for mapping energy and material flows in their manufacturing plants?	
Interviewee	**Well, both energy and mass, I don't think so. .. Within mapping flows, I don't think so**. The auditing companies in France forced them to look at the consumption of energy as it does arrive within the companies, and it forces them to, let's say have indicator of energy efficiency for the company. **It was quite challenging for some companies to define sensible and meaningful indicators at really looking at flows of energy and apart from that also flows of mass, I'd really doubt. I really doubt they do.**	02
Researcher	You initially said that the industries that you mentioned you were involved with, so I guess you have looked at quite a few companied right? How many roughly?	
Interviewee	Overall, the voluntary agreement looked at 200 companies. I couldn't visit all of them, I was not responsible to look the energy of the individual companies, my colleagues did.	
Researcher	So what you understood, to confirm, is that there was no systematic way to look at energy and mass flows and there was no tool used to map such flows?	
Interviewee	No. somehow, **it was suggested to use Sankey diagrams within their energy plants so I would say that is one of mapping energy flows**. .(not clear), but the its just talking about energy flows. **For the mass flows, I might a have feeling that have some specialised goods for it, as it really the core of the process**. The things they produce, they should know, how things are dealt with within the company and … I get the feeling there is a natural incentive to measure and it try to minimize that. Lets say you are trying to make a care and lets say you have ten steps procedure and if you have some failure at step	02

	number eight, then it must annoy them. I think especially in car manufacturing, there is something like a six sigma quality approach. And as I said in those that companies that have complex machinery with the six sigma approach they try to limit production of (not clear word) products.		
Researcher	Based on the triple bottom line approach, sustainability depends on social, environmental, and economic aspects, and in your experience how would you rate those in a total marks of ten with regards to its importance for the company, and in the sense of what would drive their sustainability measures.		
Interviewee	**In general I would say, 6 for economic, 2 for environmental and social each**. Also, there are variations for example there are companies that try to set an example within the limits of what is economically feasible. **There are some companies that are very proud of their intervention in the social aspects** and try to have a good relation with the collaborators and also with the people involved. **Perhaps 6 to economic is too pessimistic, at least I would give five to economic aspects**. Because for social, if you don't have a good relation with the collaborators, they can block production by going into strike. **So social needs to be avoided.**		03
Researcher	So now we move on to the second part of the interview, which is specific to my approach. Basically, in my PhD I am saying that I we use this approach for a factory's resource efficiency analysis, then you can make the factory operation more sustainable. So would you like me to quickly go through the slides I sent before just to refresh your memory?		
Interviewee	Sure		
Researcher	The slides are described to the interviewee, main points summarised as , 1 – combined assessent of mass and energy 2 – unified indicator 3 – holistic approach (example provided to explain) Case studies are explained to refresh the knowledge for the interviewee	Description of the research provided to the interviewee	
Interviewee	**In the engine cylinder production HVAC study, why not add an option which does not have heat recovery, but only solar power.**	(this option was then added later, after this feedback, and the webinar's)	

Researcher	That is good point and I will consider it. Further explanation continued…		
Interviewee	With the jaggery case, how do you allot exergy to products? How do you do that? If a product is processed, how do you calculate the exergy of that?		
Researcher	(Explanation of the jaggery process) - only the thermal exergy has been calculated … (further explanation of the answer)	The interviewee identified some gaps and raised some issues that were addressed at a later stage of the research.	
Researcher	How understandable do you find the concept of exergy, on a scale of 1-10		
Interviewee	**Personally, I am chemical engineer, and I had thermodynamics while being a student at university so I do understand the concept quite well. So, 8.**		04
Researcher	With regards to identifying resource saving opportunities in a factory, if you were to compare to approaches, one based on energy while the other on exergy, how would you comment on the comparison?		
Interviewee	Well, just from a practical point of view, I see people struggling with the energy concepts in a factory and how can they deal with exergy aspects, so, **I think from a practical point of view, its very challenging**. As you just indicated yourself that allocating exergy to products can be challenging and is not straight forward. **That is one of the main barriers I do see**. In general, one can say the higher the quality, the higher the price. **But this is not always the case, as at some points, power can be cheaper than natural gas. In the city of keul, they started inserting electric boilers within the heating grid to replace natural gas. So they are using electricity to heat up water to 100 degree Celsius which is not very exergy efficient. But from an economical point of view, there was so much wind power that they really needed to discharge it**, so they could use it to heat up water at very low prices. I use this example to show that a lot of the times, it all about economics.		04 07 07
Researcher	**Can you comment on the holistic nature of the approach? Would it be Beneficial or not?**		06
Interviewee	**Yes I think it would**, I think it has been used in another		06

	way in the **pinch approach**. It tries to do that to some extent, is a practical way of doing that, and even that it looks at the energy exchange between the different parts of the company also looking at the temperatures and also (not clear word) by exergy levels and **even that is challenging**, from the point of view of a company. Quite a lot of measures are implemented in which heat is recovered, to use waste heat to heat buildings or drying purposes,	07
	It's beneficial, but practically, you are a bit limited because of the complexity. And I am not sure that you can apply it so widely as an energy audit. **You need energy auditors who can understand the concept and who can easily and who can implement the methodology in the different cases they are confronted with, and I am a bit sceptical about that**. **Nonetheless, if you analysis in some ways, like you did in the case studies, then it can help, as in this case the jaggery sector, and to make them aware of the possibilities.**	07 07 06
Researcher	Why would you think it is necessarily beneficial to take a holistic approach?	
Interviewee	**Well, I assume it makes them aware of the possibilities of saving energy.**	06
Researcher	Could you comment on the suitability of an exergy based with regards to identifying surplus resource in a factory, in comparison with an energy based approach?	
Interviewee	**If it's as easy to implement as an energy approach, then I don't see much hindrance in using it.**	06 08
Researcher	How would you comment on the ease or difficulty of implementing an exergy based approach in comparison to an energy approach?	
Interviewee	**It is more complex, in terms of calculating the exergy of products.**	07
Researcher	If someone understands the approach perfectly well and somehow overcome the issue of product's exergy, and could apply it practically, do you see any other hindrances? Data collection related etc?	
Interviewee	**Time consuming and have costs which can be quite considerable** and then you must have the money to spend on that kind of study so the results of that study lead to savings which are considerable enough, then OK.	07
Researcher	**So you are saying that considering the issues, you would rather look at mass and energy separately than on a common basis.**	07
Interviewee	**Yes**	

Researcher	Could the presented method bring useful insights for your organization?	
Interviewee	I am not that much involved in energy audits of companies, I look at it form a higher level.	
Researcher	Any suggestions to improve the approach?	
Interviewee	First of all, I need to read your paper to understand you analysis better, so to understand the high complexity of it and its value. I would suggest look under those aspects. **What does this methodology add compared to classic energy audits**. And what would it costs to carry out such studies.	09
Researcher	Discussion about data acquisition and cost, (no new data).	
Researcher	Do you think a step by step exergy audit methodology which an auditor or factory manager could apply would be beneficial in terms of adding value to the approach.	
Interviewee	**Yes – if you could demonstrate it practically**	09
Researcher	Could you expand please?	
Interviewee	**Because you are in direct contact with personnel form companies themselves, you could understand what motivates them to test it. And how this methodology might respond to their needs.**	08 09

Interviewee #2:

This interviewee had extensive energy auditing experience, 30+ years within Europe.

Table 34 - Interview #2 transcription

Person	Transcription	Code	Notes
Researcher	So as an expert you look at the resource efficiency and energy efficiency of industrial settings?		Starting sentence missing in recording, but description of interviewee role captured.
Interviewee	Mostly, **only energy efficiency so those things that relate to material efficiency, that's not so much my field.**		
Researcher	So, its only energy efficiency and not the overall sustainability of the factory?		
Interviewee	Yes, mostly its energy efficiency. I did do some energy audits in my previous work, but now in Motiva, we don't do any audits. We just give advice to those people that are auditing.		
Researcher	The first part of the interview is going to be		

	a short one, and I just want to get your view on what the industry understands about sustainable manufacturing. Following that, the interview will be about comments around my developed approach.	
Researcher	How would you define sustainable manufacturing? Do you think in your experience when you conducted energy audits, was it something important and clearly understood?	
Interviewee	**I think, the first, most important thing is the quality of the products, and then after quite a big gap, comes energy efficiency. Sustainability is at the same level as energy efficiency, material efficiency and so on, but the first priority is the quality of the product.**	01
Researcher	From your experience, can you scale on a range of one to ten, how clearly sustainable manufacturing is understood, and how important is it on a scale of one to ten. ?	
Interviewee	It depends very much on the factories, in some cases it was not that important, in other places where energy was used very much, it was much more important. **I would say, the average is around 8.**	01
Researcher	So, generally, quite high then?	
Interviewee	Yes, quite high, in Finland we have this long and cold winter, and that one of the reasons which raises the energy costs and companies want to be energy efficient so that why	
Researcher	In the companies that you have visited, were they only interested in energy efficiency or did they consider material flows, such as water consumption to be important?	
Interviewee	**Yes, everything that cuts down the costs is interesting and if you turn down the water consumption, then it may be very useful and cost effective.** You might get water that is higher in temperature and that might be used in some other processes, so that might be circulating cooling water in processes. When you have water at 20-35C out coming, its much useful for other purposes.	02 03
Researcher	Judging from your comments, I assume	

	material flows were considered separately to energy flows.		
Interviewee	**Yes, right now, energy audits are different from material audits but in material audits it's kind of integrated in the audit, but then material audits, they don't for example pay attention to compressed air (wastage**). It only looks at how it is used but they don't look into the compressor room or the boiler room. They just use those services.		Wastage of compressed air was implied
Researcher	In your experience, were there any specific tools for mapping energy and mass flows?		
Interviewee	**We have some, and most of the consultants have their own tools which they don't actually share with other competitors, but then there are also the commercial and freeware software that they use**. But I'm not sure which are the most popular and the most used?	02	
Researcher	For the drivers of sustainability, among social, economic and environmental issues, how would you distribute marks among them based on how important they are for the industry?		
Interviewee	**Economic is six, and environmental and social, two and two each… money talks!**	03	
Researcher	Now that we coming to the second part of the interview, I would like to explain my approach. (explanation of the novel approach) - Holistic - Exergy approach o Common units - Resource efficiency accounting - Case studies explanation		
Researcher	Do you have any questions about the approach?		
Interviewee	**With regards to the automotive case study, I get kind of confused by the, because I am used to dealing with energy efficiency etc and now you have this exergy destruction and this is something I have been dealing with and previous time I was dealing with exergy was round 30 years ago when I studied in the university**. But this exergy	04	

	destruction is an interesting view, but its kind of confusing because I have been looking at things for a different point.	
Researcher	You actually answered my next question, which was how understandable do you find the concept of exergy, so just to confirm, as far as practitioners in the industry, the exergy concept is not much understood?	
Interviewee	**I think if you go to a factory and you say that you are using exergy as your basic unit, I am sure all of them will be very confused, maybe one of fifty engineers know what you are talking about.** So its very seldom dealt with and even in people who are doing energy audits, they are not familiar with this thing.	04
Researcher	Description of the jaggery case study and some extra explanation about the exergy concept… Was that useful?	
Interviewee	**Yes, this is extremely clarifying slide because you can compare these two things in a very simple and common way. There is nothing mysterious, so it's very useful. If I go to the factory with this slide, I am sure it will help people understand what energy is and how it differs from exergy.**	04
Researcher	So, now that you are clear about the concepts of energy quantity and quality, in your experience, with regards to resource savings identification, how would you compare the two approaches? One that is based on energy to that of one based on exergy?	
Interviewee	**Compared to my background, I would certainly choose energy audit, this exergy is so much different and I haven't used it my work but on the other hand it gives very interesting views for comparing these two methods and quite surprising results to those expected as in your presentations**, they were not at all would you expect just from the beginning that changes would be so big and what would actually be the difference. And I think, energy audit, at least	04 05 06

	for one person who hasn't done exergy audits, are much harder to go through for those who have not done exergy audits before. **And I think there is a preparation for finding useful values for chemical exergy etc. they are not found like this energy specific heats etc**. you have to do some work to find the proper values.		The online database (exergo-ecology portal) could be a useful resource in this regards.
Researcher	Do you think this holistic approach would give you clearer insights into resource savings for a factory?		
Interviewee	**Yes, yes I think this exergy gives this view what is left of the energy and how the surplus heat can be used in a different integration with parts**. It is not that clear **when you do some changes, it all for the best**, but like in this jaggery case, it was kind of surprising how this picture changed when you deal with exergy. And this is what I found kind of, makes you interested in what is happening in this process. What is the best way to approach to understand and this is why this exergy audit I think has some disadvantages that it not so commonly used because people who read the reports are not so familiar with this thing. **But if it's taught in universities or when studying (before university) would learn what are the insights of this thing then when they are in work life etc.** they would have the basic knowledge of this thing, I would be much easier to present these results for them.	05 06 08	
Researcher	In circumstances when chemical exergy calculation is not required, then complexity reduces.		
Interviewee	Yes but the thing is, let's say in simple way the temperature level of waste heat, it's easier to understand that exergy destruction.		
Researcher	Do you think when you looking at the whole factory holistically on a common unit basis would have any benefits or would it be more beneficial to keep these separate? For example it might yield a combined indicator		

	however some people might want to keep them separate.	
Interviewee	**Hmm… I think it would be better to combine because then you see the whole thing at one time than if you take them in two parts then it's kind of what is happening here, what is happening there, and you don't know how they combine together.**	06
Researcher	In your experience of visiting factories and conducting audits, if you had the option to apply the exergy method in a current project, then can you think any useful application in a current situation that you are analysing? Because you did mention the exergy method could be useful, but can you think of a useful practical application in a current project that you involved with?	
Interviewee	**In an industrial furnace, and in different factories, a glass factory, food factory etc. and I think that furnaces especially in the food area I think, there might be some interesting cases where this would be useful, because there are quite low temperatures, then there is steam, then there is cooling water, all this baking and boiling and what is happening in the ovens, and this surrounding might be interesting for this type of study.**	08 05 06
Researcher	If you think it would be interesting and useful, then how do you think it would be introduced effectively because as you said, when they hear about exergy, they think of it as something that is mysterious. So you do you think it could be introduced effectively?	
Interviewee	First of all, before you have to, kind of present what is an exergy and then compare it to an energy audit and let them kind of order both of those at the same time because that way they could get the results which they clearly understand the they would get the results which they don't probably understand so much but they would get the benefits from it. **Like the food industry, they have usually, they don't have**	

	one furnace they have maybe twenty with ten different types of furnaces, if you get one kind of done in two ways, and energy and exergy audit then this is a way that you could get results and kind of sneak into the factory.	08
Researcher	**So basically, small practical steps?**	
Interviewee	**Yes – absolutely, there is so much stubbornness and people stick to their old habits**	07
Researcher	Do you think a step by step exergy audit methodology would help it applicability to the industry? A guide that is similar to an energy audit, would it help?	
Interviewee	**Yes, and also I think there should be some public seminars where exergy audits and exergy is presented and people get to know what is behind this word.**	08
Researcher	Do you have any suggestions for improvements regarding the presented exergy based approach?	
Interviewee	No, I just think, I just put some ideas in my notes. And first is I mentioned, is,… **money talks..** **In industry people wants quick results and this is one obstacle in this exergy audits to become more popular.** Then this was the control volume boundaries of the target that we are looking, this is very important thing. Like in you presentation, how you describe your boundaries, you get different values. Depending on how you select you boundaries.	07 08 07
Researcher	Thanks, there are very useful comments and I will try to incorporate them. For example, if the economic aspects could be incorporated into the approach and provide results that are more representative of reality as compared to an energy audit, then that could be a step in the correct direction.	

Interviewee #3:

This interviewee is currently an academic working in the area of energy and resource efficient manufacturing; however he worked previously as an energy auditor. Relevant experience of this interviewee was more than 10 years.

Table 35 - Interview #3 transcription

Person	Transcription	Code	Notes
Researcher	Can you please explain your role for your organization?		
Interviewee	**I am a university lecturer, associate professor and I have about 80% of my time devoted for research. I think ten different research projects that I am involved in now and a few which I am also responsible for. I also have 20% dedicated for teaching, so that's about my role. In relation to sustainability of course, it is an emerging field of research and my field is improving energy efficiency in the industry which is one of the three major means to improve sustainability from a top down perspective.**		Interviewee profile
Researcher	So that means you have a lot of experience of practical situations and real case studies?		
Interviewee	Yes, that is correct. I have been working previously as an energy auditor for a few years and, I have also been extensively involved in energy policy work that has been going on in the Swedish government. **So I have both experience form the policy and the field but also from the real world.**		
Researcher	The first part of the interview is generally about manufacturing. How would you define sustainable manufacturing?		
Interviewee	**The definition of course is that manufacturing that is as resource efficient as possible.** From my perspective, without discarding the	01	

	other perspective, I am basically doing research only on sustainable manufacturing sites which I call the horizontal perspective, and not the vertical perspective which is crucially important, the role of highly sustainable products that comes out from the manufacturing process.	
Researcher	In your experience as an auditor, how important and clearly understood is sustainable manufacturing. If you could scale its importance from 1-10 it would be good.	
Interviewee	This may be a long explanation, but **my major research since seven years has been on improving energy efficiency in small and medium sized companies, which is 99.9% of the European companies**. **The sustainability in a company today, you have to understand that it cannot become core business within a manufacturing company**. It can be if you put the trademark on the actual products, based on the definitions of core competence, a competitive edge that is difficult to copy from a competitor perspective but basically, sustainability in Sweden, we have had a culture where very many companies were ISO 14000 certified. Now the numbers are starting to decline. I think we were the worlds more ISO14000 certified country per capita in the world but now this is starting to decline a little bit. For companies that are large, I would say they are doing quite well, and good work in terms of sustainability. **For the rest 99.9%, I would say a rating of three, but then I am quite kind**. For large companies, they are quite well in terms of this and they also have a full dedicated staff for this, but for the large majority which is small and medium sized, I would say a grading of three out of ten would be a maximum	01 01

	in terms of importance.	
Researcher	When looking at resource efficiency, in your experience, are mass and energy flows considered separately or in a combined way?	
Interviewee	I assume you are doing something like life cycle type of research and then you a good idea about the birth to the grave, **my experience is on a horizontal level and I have never seen a mass balance ever. I mean, I have, when we publish papers on this from researchers looking at exergy analysis, of course they would have mass balances but the normal person deployed form the consultant, its only energy flows that are considered.**	02
Researcher	Ok, so when they are considered, are there any specific tools for mapping flows?	
Interviewee	**Yup, we have energy audit software, which is a mapping software that you see a taxonomy**, that has been developed here in 1994 in this research division. So the software is based on that**. It is called nordon audit, 2.0.** I am quite involved with that company so if you would like to have a liscense, you just send me an email.	02 02
Researcher	Could you distribute ten marks among the three drivers for sustainability, social, economic and environmental?	
Interviewee	I came back from a workshop in Tokyo roughly one week ago, and **I think the answer is very contextually based**, **because in japan, they don't see their company or themselves as the major emphasis, they see their country**. So, if you ask a Japanese researcher, he or she would say that, it's all about the social aspect and the nation-wide aspects for that country, that is why so much emphasis is on context. I have never faced this in Europe and absolutely not in Sweden but having said that from a	03

	Swedish perspective**, I would say if sustainability by an economic perspective is simply not there. You don’t earn more money by having it,** sustainability work and energy efficiency work often very separate because the energy work is made by either the production or maintenance division while the sustainability work is often up higher in the …(not clear).. Environmental executive cannot even distinguish between kilowatt hours and kilowatt. So this means that if we want to see the impact of sustainability excluding energy, normally or often is the case, my bias, then social environment will be fifty fifty. **If we include energy in sustainability, I would say one third of each of those will be the driver.**	01 03	
Researcher	Moving on the second part of the interview, specific to my developed methodology for factory resource efficiency analysis… (explanation follows) - Holistic approach - Exergy approach - Case studies Any questions?		
Interviewee	Just… when It comes to improving overall sustainability I didn’t really catch what you did but my perspective in theory incudes the conversion of energy carrier and it includes more energy efficient technology and it also involves more efficient management operation, that is often totally missed by us engineers who doing studies on energy efficiency and resource efficiency that is the operation and control of technology that we have implemented. It might be out of topic but it may be worth maybe one sentence, because the potential for that might be even higher when it comes to highly energy intensive processes		

	because they seem to (not clear) for new investments, lets say 100 million euros in the production line then its much more efficient to educate the staff to be more efficiency in their operation.	
Researcher	**So, just to confirm this important point, the social aspect is very important as even if you install energy efficient technology but if people don't use it properly then your efficiency gains would not be that high.**	03
Interviewee	**Exactly**	03
Researcher	(Explanation of the second case study) Any questions?	
Interviewee	No, but I think your results are very interesting and they seem to me to be of general nature, I mean you could generalize based on this case study which would make the paper or your thesis a lot more solid. But to my awareness, we have no sugar plants in Sweden, there might be one but I have not been there, I have not visited a sugar factory. I get the view, exergy and balance and so on.	
Researcher	Some further explanation about the jaggery study results	
Interviewee	I have one comment, based on my previous comments, **we did an energy audit for our university division for a foundry and what happened was that they established an energy group at the foundry. So, we had to evaluate that how many of the measures they had implemented that we had proposed. In this group that was established, the manager of the foundry was always there and this made all the other managers show up as well. And the melting division manager, he got some inspiration so he made his staff to charge the furnace with iron right after they had emptied the furnace. This simple measure improved the energy efficiency of melted metal per ton by**	03

	10%. It was a pure operational measure, speaking about furnaces in general, here you have this example of management that we as engineers don't take into account but there might be potential for we as researchers for the future.	
Researcher	Yes – we have to look at aspects other than only numbers.	
Interviewee	The other thing is, I have a PhD thesis from my division that is maybe ten years old but it regarded exergy analysis in industry… I don't know if I have it around but maybe… just one minute Ill email you the title, you can have a check on it.	
Researcher	Ok, so we will go to the next question. How understandable to you find the concept of exergy? Also, how well does the industry understand it?	
Interviewee	I know that here in Sweden, **the company, SSAB melt metal, I think they have done exergy analysis at their factory. I think they published an attitude paper on exergy analysis in the industry from the applied energy conference.** I can see if I can show it to you right now, I was not the main author, we called it, **a stakeholder study on barrier to exergy analysis**…	04 07
Researcher	Thanks, I think it should be really good in order to see how people perceive exergy. With regards to resource savings, how would you compare two approaches, one of which consider energy quality only, whereas the other used quality and quantity?	
Interviewee	Well, you probably herd this of course, the problem is that the industry is in an economic context. They are not so much energy weirdoes as we are; the analysis of exergy, **with energy quality and quantity is inhibited to a large extent by the fact the we pay for quantity, not for**	07

	quality. Whether that calls for a change in the economic constitution… that far beyond my level of knowledge, but I think that is my view on the comparison. **Energy quantity is used in an audit, in the core reporting to the company, quality is hardly ever covered.**	
Researcher	With regards to identification of resource saving opportunities, could you comment on it in that regard?	
Interviewee	Of course, **taking the 1st and 2nd law of thermodynamics is desirable, of course then we could really speak about resource efficiency. If we skip the quality part, we are actually doing a kind of a shallow work.**	05
Researcher	**Do you think a holistic approach is useful in this regards as well?**	
Interviewee	**Yeah – absolutely. A great yes.**	06
Researcher	Could you elaborate please	
Interviewee	Of course, if you look some years back, the major issue with sustainably has been to improve the supply of green energy. And then finally, we understood that we should try to improve the use of energy that we have, that we are using. Then still, we are speaking about energy and not exergy so, **including both laws of thermodynamics, I mean that should almost be written in stone, when it comes to sustainability**. You are comparing Japanese yen with dollar bills, you are just speaking about money and you are missing out on value.	05
Researcher	With regards to application, its ease or difficulty, how do you compare the exergy approach with the energy one? … for applying it in the real world.	
Interviewee	Personally, I have not done an exergy analysis of a factory, I have only (missing words), publications, primarily, it is a Dr. Vall, **I cannot say anything about the difficulty actually**.	
Researcher	If you could use exergy analysis in your organization, your research department,	

	could it bring useful insights? If it could, then could you gave an example?	
Interviewee	As I said, we have covered exergy analysis in our research quite a long time ago, **what happened here in Sweden, it was that, Dr. Vall in Chalmers published his PhD from Chalmers and he promised that this is the new way to use exergy basically, but that's not so much happened really. So the concept is just rock solid, but when it comes to application in the real world, it is not a lot of value(economically)**. Then it crashes when actually applying it to the private sector. **In the university sector, its excellent, and I have also seen one work, many years ago, in the farming industry, what I recall is agriculture, and it was brilliant. They used the exergy approach there as well, it brings excellent insights, but then, how these insights are deployed has been a great disappointment.**	07 07
Researcher	So if these insights are there, why isn't the industry acting? How could we effectively introduce the concept of exergy in the industry so that the insights could be converted into some action?	
Interviewee	Well, if I would have answered this question, say ten years ago, I would have given the answer which is the most common answer given by engineer, policy makers and economists. That is to provide information campaigns, raise awareness and then things change. But **if you are to gain cultural transformation, for any concept, it always starts with the theory and education. In this case, most manufacturer, they don't even know what exergy is, so I think having to introduce it effectively, firstly would be to include it in the school system. Not only energy, but exergy, not only at university level, but in elementary**	

	school and onwards. Secondly, the whole system of valuing energy and not its quality of course needs to be reformulated and that is a political issue that I am very doubtful it will ever happen. But then, that would also have to be taken into account or **the research community needs to develop methods so that, when we speak about sustainability, we don't only speak about quantity but also about quality. That could also develop the methods**, for example, the methods today don't apply quality so these two issues, I will stop there. I don't believe in information campaigns for exergy analysis	07 08	
Researcher	Finally, do you have any suggestions for improving the approach, other than the social aspects and impact on operational management?		
Interviewee	I think it is a very interesting work to do exergy analysis and **it really calls for future research**, **not the least case studies.** I think you are, really, really on the way and (not clear word), answering the question, of course a methodology would of course be very interesting **and I think the study we did on barriers and drivers for exergy analysis could also be one further study to be done within the UK**. **Having a questionnaire rather than having semi-structured interviews, asking, guys why you are not deploying exergy. That could provide some insights, but really it would be for academics, than changing or increasing the use exergy analysis.**	09 07 08	
Researcher	**Do you think a step by step exergy audit methodology would help in its practically acceptance and usefulness for industry?**		
Interviewee	**Yes**	08	
Researcher	Of course, it would be difficult to have one methodology due to the variation in processes.		Abdriged version of researchers expliantion

	I guess if you would have a comprehensive exergy audit methodology, it could be useful.		
Interviewee	**Absolutely**.	08	
Researcher	Thanks, there are no more questions; your feedback was very valuable.		Abridged version of ending the interview by the researcher

Interviewee #4:

This interviewee is a high level resource efficiency manager at a large global aircraft manufacturer. However, due to the circumstances of the meet and his commitments, the interview could not be transcribed. Additionally, a brief description of the methodology devised in this PhD was presented, rather than a detailed description. Nonetheless, the major points that emerged from the discussion and presentation of the devised approached were noted down. Following are the salient points of the interview,

Researcher question regarding the utility of a Unified indicator:

Not really, as it probably does not represent the whole situation accurately enough. In Airbus, different indicators for mass, energy and water flows are used, that are used to monitor resource efficiency.

Firstly, how could be it be combined, and if it is done so, it would be not good at finding the locations of the in-efficiencies occurring.

Researcher: Could the approach be useful to your organization?

I cannot say, it might be but I cannot say unless it is tested in the facility. The holistic exergy approach might be useful, but, again, cannot say unless implementation in practice is tried.

Researcher: Have you heard, or used exergy before?

Studied it at university, and had a brief look at the concept a couple of years ago, however don’t know in detail and would like to hear about it more.

Appendix 4

This appendix provides the written responses acquired during the qualitative study presented in chapter 8.

This appendix presents the data collected during the qualitative assessment of the novel devised factory analysis methodology. As the data were collected in three different formats through different methods (LinkedIn and Survey monkey), the information is provided for each as follows.

LinkedIn Responses:

LinkedIn was used to contact people in factory management positions that were involved with either resource efficiency of sustainability at the factory. In order to get maximum responses, some short questions were asked, the responses to which are provided in table xxx. The questions themselves are as follows,

1 - Would a unified indicator for resource efficiency be valuable to your company, or manufacturing in general?
2 - If it is valuable, why? If not why not?
3 - Have you come across the concept of exergy to quantify resource consumption?

Table 36 - LinkedIn responses collected

Serial No.	Respondent's role	Respondent's answer
1	Environmental Programmes Manager at BMW Group	1) I can't see the value in a single metric. There are too many variables to consider to lump them all together IMO. Almost like an EPC energy rating a building may be a 'C' but this only gives a fraction of the story. Or you could be ultra efficient in water saving but not energy - one metric could artifically inflate or deflate the other. 2) See above - not enough key target metrics, therefore targeted reduction may become more difficult . 3) I have not heard of exergy.
2	Sustainability manager at ABB	We don't have a unified indicator, but many. One single indicator can often be misleading. I used the concept of exergy when dealing with LCA.
3	Global Packaging Sustainability	1. to be honest I'm not sure this is the answer you are

	Manager at SABMiller	looking for, but SABMiller, were possible consider CO2e impact as an indicator of resource impact. - if you look up SABMiller Prosper, you will find more information 2. Increasingly our stakeholders are keen to find a tangible numerative measure for sustainable development activities, CO2e impact is one, but not the exclusive measure. In most cases our measurement reverts to financial impact. 3. I have not. I would be keen to hear more.
4	Country Head of Energy & Sustainability at COFELY	I don't think a unified indicator for resource efficiency would be particularly useful. There are a number of indicators already used such linking energy use to variables in industry such as units of product, degree days, cost per hour of operation, energy use per occupant etc. Our clients can choose which one fits their drivers best and use that for reporting. I'm not sure there could be a unified indicator that would fit all applications. I have come across the term exergy in thermodynamics as the amount of energy that is available to be used, but in 10 years of working in the field of energy management, I have not come across it used to quantify resource consumption.
5	Associate Director at CorEnergy Limited	We have made several attempts over the past few years to develop a unified resource efficiency indicator internally. However, as yet we are having trouble getting our manufacturing sites to accurately account for i) raw material mass inputs, ii) cross site exchange of partially finished goods, iii) converting all inputs into a single consistent and agreed measure (kwh embodied energy for example) and in some cases iv) accurate measurement of outputs (waste and production volumes – production volumes tend to get rounded up to the nearest 500000 units, and some sites just don't track their waste very effectively). However, it is an ongoing effort.

	We believe that it would be an excellent way of demonstrating full-life cycle production efficiency and to identify areas for improvement. We have heard of exergy (as in the total amount of energy available) and that partially informed our thoughts towards the total embodied energy of inputs and outputs, to help develop a resource efficiency ratio. However, as mentioned before, we are struggling to gather data of sufficient quality to be happy using it.

Survey feedback from presented webinar:

A webinar was presented to an audience who were interested / working in the area of resource efficient manufacturing. Following are the survey responses.

Respondent 1:

Q1: Please select the one closest to your job title

other

Q2: Would a unified indicator for resource efficiency be valuable to your organization?

Yes

Q3: Please explain your answer to question 2 (Optional)

Helps in wastage management

Q4: Have you come across the concept of exergy for quantifying resource consumption?

No

Q5: Please describe your answer to question 4 (Optional)

Nil

Q6: Would the presented approach be useful to your organization?

Yes

Q7: What do you think are the major drivers and barriers to the implementation of the presented approach?

No ideas

Q8: Could you please suggest any improvements to the approach?

No ideas

Respondent 2:

Q1: Please select the one closest to your job title

Academic

Q2: Would a unified indicator for resource efficiency be valuable to your organization?

No

Q3: Please explain your answer to question 2 (Optional)

one indicator would never provide sufficient detail to act upon. There are also many meanings of the word efficiency for many different purposes and so there is no one-solution-fits-all.

Q4: Have you come across the concept of exergy for quantifying resource consumption?

Yes

Q5: Please describe your answer to question 4 (Optional)

I have used it in my research.

Q6: Would the presented approach be useful to your organization?

Yes, it is a useful contribution

Q7: What do you think are the major drivers and barriers to the implementation of the presented approach?

a major barrier would be that industry generally don't understand energy very well and so exergy would be even more confusing. Also energy/exergy is typically a very low expenditure for companies and so they are more interested in other opportunities.

Q8: Could you please suggest any improvements to the approach?

Highlight additional benefits - e.g. able to rely on local renewable energy or optimise production time, or reduce need for replacement of equipment, etc.